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„Es ist eine Frage, ob den Wissenschaften und Künsten ein Bestes möglich sei, über welches unser Verstand nicht gehen kann. Vielleicht ist dieser Punkt unendlich weit entfernt, ohnerachtet bei jeder Näherung wir weniger vor uns haben.“

[“The question arises as to whether the sciences and the arts can reach a pinnacle that can never be eclipsed by reason. We are, perhaps, infinitely far removed from this point, although our striving continually brings us closer.”]

– Georg Christoph Lichtenberg –

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Summary

This thesis investigates the relationship between eye movements, memory and thinking in five studies based on eye tracking experiments. The studies draw on the human ability to spatially index multimodal events as demonstrated by people's gaze reverting back to emptied spatial locations when retrieving information that was associated with this location during a preceding encoding phase – the so called "looking-at-nothing" phenomenon. The first part of this thesis aimed at gaining a better understanding of the relationship between eye movements and memory in relation to verbal information. The second part of this thesis investigated what could be learned about the memory processes involved in reasoning and decision-making by studying eye movements to blank spaces.

The first study presented in this thesis clarified the role of eye movements for the retrieval of verbal information from memory. More precisely, it questioned if eye movements to nothing are functionally related to memory retrieval for verbal information, i.e. auditorily presented linguistic information. Eye movements were analyzed following correct and incorrect retrievals of previously presented auditory statements concerning artificial places that were probed during a subsequent retrieval phase. Additionally, eye movements were manipulated as the independent variable with the aid of a spatial cue that either guided the eyes towards or away from associated spatial locations. Using verbal materials elicited eye movements to associated but emptied spatial locations, thereby replicating previous findings on eye movements to nothing. This behaviour was more pronounced for correct in comparison to incorrect retrievals. Retrieval performance was higher when the eyes were guided towards in comparison to being guided away from associated spatial locations. In sum, eye movements play a functional role for the retrieval of verbal materials.

The second study tested if the looking-at-nothing behaviour can also diminish; for example, does its effect diminish if people gain enough practice in a retrieval task? The same paradigm was employed as in the first study. Participants listened to four different sentences. Each sentence was associated with one of four areas on the screen and was presented 12

times. After every presentation, participants heard a statement probing one sentence, while the computer screen remained blank. More fixations were found to be located in areas associated with the probed sentence than in other locations. Moreover, the more trials participants completed, the less frequently they exhibited the looking-at-nothing behaviour. Looking-at-nothing behaviour can in this way be seen to indeed diminish when knowledge becomes strongly represented in memory.

In the third and fourth study eye movements were utilized as a tool to investigate memory search during rule- versus similarity-based decision-making. In both studies participants first memorized multiple pieces of information relating to job candidates (exemplars). In subsequent test trials they judged the suitability of new candidates that varied in their similarity to the previously learned exemplars. Results showed that when using similarity, but not when using a rule, participants fixated longer on the previous location of exemplars that were similar to the new candidates than on the location of dissimilar exemplars. This suggests that people using similarity retrieve previously learned exemplars, whereas people using a rule do not.

Eye movements were used yet again as a tool in the fifth study. On this occasion, eye movements were investigated during memory-based diagnostic reasoning. The study tested the effects of symptom order and diversity with symptom sequences that supported two or three contending hypotheses, and which were ambiguous throughout the symptom sequence. Participants first learned information about causes and symptoms presented in spatial frames. Gaze allocation on emptied spatial frames during symptom processing and during the diagnostic response reflected the subjective status of hypotheses held in memory and the preferred interpretation of ambiguous symptoms. Gaze data showed how the diagnostic decision develops and revealed instances of hypothesis change and biases in symptom processing.

The results of this thesis demonstrate in very different scenarios the tight interplay between eye movements, memory and thinking. They show that eye movements are not automatically directed to spatial locations. Instead, they reflect the dynamic updating of internal, multimodal memory representations. Eye movements can be used as a direct behavioural correlate of memory processes involved in similarity- versus rule-based decision-making, and they reveal rich time-course information about the process of diagnostic reasoning. The results of this thesis are discussed in light of the current theoretical debates on cognitive processes that guide eye movements, memory and thinking. This thesis concludes by outlining a list of recommendations for using eye movements to investigate thinking processes, an outlook for future research and possible applications for the research findings.

Zusammenfassung

Diese Dissertation beschäftigt sich mit der Interaktion von Blickbewegungen, Gedächtnis- und Denkprozessen. In fünf experimentellen Untersuchungen, die auf der Messung von Blickbewegungen beruhen, wurde die menschliche Fähigkeit zum räumlichen Indizieren multimodaler Ereignisse untersucht. Diese Fähigkeit manifestiert sich u.a. im sogenannten „Looking-at-nothing“ Phänomen, das beschreibt, dass Menschen beim Abruf von Informationen aus dem Gedächtnis an Orte zurückblicken, die in einer vorhergehenden Enkodierphase mit den abzurufenden Informationen assoziiert wurden, selbst wenn diese räumlichen Positionen keinerlei erinnerungsrelevante Informationen mehr enthalten.

In der ersten Untersuchung wurde der Frage nachgegangen, ob Blickbewegungen an geleerte räumliche Positionen den Abruf von Informationen aus dem Gedächtnis erleichtern. Während ein solches Verhalten für den Abruf zuvor visuell dargebotener Informationen bereits gezeigt werden konnte, ist die Befundlage für die Erinnerungsleistung bei auditiv dargebotenen, linguistischen Informationen unklar. Um diesen Zusammenhang zu untersuchen, wurde das Blickverhalten zunächst als Folge von richtigen und falschen Antworten untersucht. In einem weiteren Schritt wurde das Blickverhalten experimentell manipuliert. Dies geschah mit Hilfe eines räumlichen Hinweisreizes, der die Blicke entweder hin zu der Position leitete, die mit dem abzurufenden Stimulus assoziiert war, oder weg von dieser Position. Die Ergebnisse dieser Untersuchung konnten bisherige Befunde zum Looking-at-nothing Verhalten replizieren. Zudem zeigte sich, dass beim korrekten Abruf von Informationen aus dem Gedächtnis vermehrt Looking-at-nothing gezeigt wurde, während das bei fehlerhaften Abrufen nicht der Fall war. Die Blickmanipulation ergab, dass die Gedächtnisleistung besser war, wenn der Hinweisreiz den Blick hin zur assoziierten räumlichen Position leitete. Im Gegensatz dazu war die Erinnerungsleistung schlechter, wenn der Blick von der assoziierten räumlichen Position weggeleitet wurde. Blickbewegungen an geleerte räumliche Positionen scheinen demnach auch den Abruf verbaler Stimuli zu erleichtern.

In der zweiten Untersuchung wurde erforscht, ob das Looking-at-nothing Verhalten nachlässt, wenn das experimentelle Material stark gelernt, d.h. stark im Gedächtnis repräsentiert ist. Dazu wurde das gleiche experimentelle Paradigma, wie in der ersten Untersuchung verwendet. Vier verschiedene Sätze wurden während der Enkodierphase mit vier verschiedenen räumlichen Positionen assoziiert. Nach jeder Präsentation aller vier Sätze, wurde einer der Sätze getestet. Diese Prozedur wiederholte sich in zwölf Durchgängen. In den ersten vier Durchgängen sahen die Versuchspersonen beim Abruf häufiger in das Feld, dass mit der getesteten Information assoziiert war, d.h. sie zeigten wie erwartet das Looking-at-nothing Verhalten. Je mehr Durchgänge die Versuchspersonen bearbeiteten, desto seltener blickten sie zu der assoziierten räumlichen Position. Demnach verschwindet das Looking-at-nothing Verhalten, wenn Informationen stark im Gedächtnis repräsentiert sind.

In der dritten und vierten Untersuchung wurden Blickbewegungen an geleerte räumliche Positionen als Methode verwendet um Denkprozesse zu untersuchen. In der dritten Untersuchung lernten Versuchsteilnehmer zunächst Informationen über fiktive Bewerber (Exemplare) für eine freie Position in einem Unternehmen. Jedes Exemplar wurde mit seinen Eigenschaften während der Lernphase mit einer distinkten räumlichen Position verknüpft. In einer nachfolgenden Entscheidungsphase beurteilten die Versuchsteilnehmer neue Bewerber. Diese neuen Bewerber variierten in ihrer Ähnlichkeit mit den zuvor gelernten Bewerbern. Versuchsteilnehmer die eine ähnlichkeitsbasierte Entscheidungsstrategie verwendeten, sahen an die geleerten räumlichen Positionen zurück, die in der Lernphase mit den Exemplaren verknüpft wurden. Wendeten sie jedoch eine abstrakte Regel an, um die neuen Bewerber zu beurteilten, so zeigten sie kein Looking-at-nothing Verhalten. Dieses Ergebnis lässt darauf schließen, dass eine ähnlichkeitsbasierte im Gegensatz zu einer regelbasierten Strategie den Abruf zuvor gelernter Exemplare bewirkt.

Auch in der fünften Untersuchung wurden Blickbewegungen als Methode eingesetzt, diesmal zur Untersuchung gedächtnisbasierter Schlussfolgerungsprozesse, wie sie beim Finden von Erklärungen für eine Anzahl gegebener Informationen auftreten. Manipuliert wurden die Reihenfolge der präsentierten Informationen und die Diversität der möglichen Erklärungen. Die getesteten Symptomsequenzen unterstützen stets mindestens zwei mögliche Erklärungen. Die Versuchsteilnehmer lernten in einer vorangestellten Lernphase die Symptome und ihre möglichen Erklärungen. Symptome und Erklärungen wurden mit räumlichen Positionen verknüpft. In einer anschließenden Diagnosephase wurden verschiedene Symptomsequenzen getestet. Das Blickverhalten während der Diagnosephase reflektierte die Interpretation der Symptome im Sinne der subjektiv wahrscheinlichsten Erklärung. Die Aufzeichnung und Analyse der Blickbewegungen erlaubte es die Entwicklung dieser Interpretation über die gesamte Sequenz hinweg zu beobachten und Hypothesenwechsel lokalisieren zu können.

Insgesamt stützen die Ergebnisse dieser Dissertation die Annahme einer engen funktionalen Verbindung von Blickbewegungen, Gedächtnis- und Denkprozessen. Sie zeigen, dass Blickbewegungen nicht automatisch an alle assoziierten räumlichen Positionen gerichtet werden, sondern dass sie vielmehr den situations- und aufgabenabhängigen Abruf von Informationen aus dem Gedächtnis widerspiegeln. Blickbewegungen können als direktes Verhaltensmaß zur Messung von Gedächtnisprozessen beim ähnlichkeitsbasierten Entscheiden herangezogen werden und liefern wertvolle Prozessdaten über die Integration von Symptominformationen beim diagnostischen Schließen. Die Ergebnisse dieser Dissertation werden im Lichte der aktuellen theoretischen Diskussion über kognitive Prozesse beim Bewegen der Augen, beim Gedächtnisabruf und beim komplexen Denken betrachtet. Abschließend werden Empfehlungen für die Verwendung der Methode der Blickbewegungsmessung als Prozessmaß zur Untersuchung gedächtnisbasierter Denkprozesse gegeben, ein Überblick über zukünftige Forschungsmöglichkeiten präsentiert und Ideen für Anwendungsmöglichkeiten der präsentierten Befunde aufgezeigt.

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1 Introduction

How do we encode and combine information from multiple modalities like vision and audition? How do we keep track of the encoded information through space and time? There is wide agreement that we achieve this by constructing mental representations of events, storing them in memory and accessing them when needed (e.g., Markman, 2012). These representations however are not entirely abstract in nature but incorporate perceptual information, such as the location of the information intake (Barsalou, 2008; Spivey, 2007; Wilson, 2002). In order to describe the interaction between cognitive processes when keeping track of multi modal events through space and time, Richardson and Kirkham (2004) have coined the term dynamic spatial indexing of multimodal events. This concept is based on several findings: (1) Spatial information is encoded with a high degree of automaticity (Andrade & Meudell, 1993; Postma & Kessels, 2006); (2) The visual system can dynamically track the locations of multiple objects as they move through space (Pylyshyn & Storm, 1988; Pylyshyn, 2001); (3) Location information is not just encoded but can be used to pick up information about visual objects or multimodal events (Ballard, Hayhoe, Pook, & Rao, 1997; Richardson & Spivey, 2000).

One consequence of dynamic spatial indexing of multimodal events is the recruitment of the oculomotor system (e.g., Theeuwes, Belopolsky, & Olivers, 2009). This can be observed in the phenomenon that multimodal memory retrieval leads the eyes back to associated spatial locations, even if the visual scenery has changed or is absent (Ferreira, Apel, & Henderson, 2008; Richardson, Altmann, Spivey, & Hoover, 2009). This tight coupling of eye movements and the dynamic updating of multimodal memory representations through spatial indexing has been called the looking-at- nothing phenomenon. This phenomenon is shown to occur under a variety of cognitive tasks, like mental imagery (Johansson, Holsanova, & Holmqvist, 2006; Johansson, 2013; Laeng & Teodorescu, 2002; Martarelli & Mast, 2013, Spivey & Geng, 2001), language processing (Altmann, 2004, Hoover & Richardson, 2008; Richardson &

Spivey, 2000) and even higher order thinking processes like reasoning and decision-making (Jahn & Braatz, 2014; Platzer, Bröder, & Heck, 2014; Renkewitz & Jahn, 2012).

Despite the extensive empirical evidence demonstrating the tight interplay of eye movements and memory retrieval of multimodal events, many questions relating to this topic remain unanswered. For example, is directing the eyes to emptied spatial locations during the retrieval of multimodal events from memory functional in the way it facilitates memory retrieval? What information is accessed during thinking? Are eye movements automatically directed to all associated spatial locations when parts of the memory representation are accessed, or do eye movements reflect the current processing status of information held in memory?

The focus of this thesis will continue in line with research investigating the interplay of eye movements and memory. Additionally, this thesis aims to investigate dynamic spatial indexing of multimodal events in more complex cognitive tasks in order to deepen the understanding of how memory processes shape our thoughts. Chapter 1 will first review existing findings and discuss current opinions on the interrelations between eye movements and memory. Secondly, this section will explain why it is important to study memory processes in order to shed light on human thinking. Thirdly, the chapter will report on existing findings in the study of eye movements and thinking. Chapter 1 concludes with an outline of the questions that prompted this research, followed by an overview of the work conducted to investigate these questions. Chapters 2 to 5 describe in detail the motivation, methods and results of five experiments and discuss their implications. These chapters are written in the style of journal articles. Chapters 2 and 4 are published in peer-reviewed journals, whilst chapter 3 is based on an article published in conference proceedings. Chapter 6 integrates the research findings and provides an outlook for future research.

1.1 Eye Movements and Memory

Why do we move our eyes? Restricting higher acuity vision to a small region of the retina and shifting the processing focus from one location to another is the solution nature has devised to cope with the vast amount of visible information barraging our visual perception (Liversedge, Gilchrist, & Everling, 2011). Eye movements are quick, frequent and highly automatic actions (Irwin, 2004; Spivey & Dale, 2011; van Gompel, Fischer, Murray, & Hill, 2007). Eye movements are not however randomly distributed. Alternatively they reflect both stimulus-driven (bottom up) and goal-driven (top down) cognitive processes (Theeuwes, 2010; van Zoest & Donk, 2004). Bottom-up processes that attract attention are object features like color, orientation, size, motion and depth (Wolfe & Horowitz, 2004). The eyes are also guided by top-down processes like task demands. Among the first who demonstrated such top-down driven eye movements were Buswell (1935) and Yarbus (1967). In Yarbus's study participants were presented with the same painting seven times, but with a different question asked prior to each viewing. He, like Buswell, observed that the given instructions radically changed the places in which the participant fixated (see Wade & Tatler, 2011).

When moving the eyes, humans use a "saccade-and-fixate" strategy (Land, 2011). Saccades are fast eye movements – they are the fastest movements the body can produce – which redirect the gaze to a new point in space. They take 30 to 80 ms to complete and vary in their velocity and amplitude. Between saccades gaze is held almost stationary. The time in which the eyes remain relatively still is called a fixation. Fixations can last between tens of milliseconds to several seconds (Holmqvist et al., 2011)[1].

1.1.1 Eye Movements and Cognitive Processing

Whereas cognitive processing of visual information essentially ceases during a saccade, a fact that has been termed saccadic suppression, information is processed during fixations (Gilchrist, 2011). This correlates with the observation that people usually look at something when they wish to gather information from that area. In general it is assumed that when we measure fixations, we gain information from or associated with the location subject to the fixation (e.g., Holmqvist et al., 2011; Irwin, 2004; Theeuwes et al., 2009). Therefore, eye fixations (fixation location and duration) seem to be ideal dependent variables in the study of cognitive processing (Irwin, 2004).

The assumption that fixation measures correspond to the duration of cognitive processing of information derived from the point of fixation was proposed in the "eye-mind hypothesis" (Just & Carpenter, 1976). This has however been an issue of debate. Irwin (2004) summarizes the discussion in highlighting four major problems to the eye-mind hypothesis. Firstly, the focus of cognitive processing can be wider than the 2.5° visual angle (De Valois & De Valois, 1980) that the fovea fixates upon (functional field of view). Secondly, the locus of cognitive processing can be separated from the fixation location, thus attention shifts earlier to a new location than the focus of the eyes shift (covert shifts of attention). Thirdly, bottom up processes can guide the eyes to a different location while processing continues (oculomotor capture). Finally, cognitive processing takes place both during eye movements and eye fixations (cognitive processing during saccadic eye movements).

On the other hand, it has been argued that the focus of cognitive processing is indeed accompanied by corresponding eye movements (Kristjánsson, 2011; Liversedge & Findlay, 2000). When task-demands necessitate it, the focus of cognitive processing can indeed be separated from eye movements. Such task-demands can take the form of an explicit

[1] Other movements of the eyes exist that serve functions beyond memory retrieval and thought processes, and will therefore only be mentioned for the sake of completeness. Those eye movements stabilize the eyes (micro movements, vestibule-ocular reflex, optokinetic reflex), allow for the following of moving items (smooth pursuit), or for the visualization of a target moving towards or away from a viewer (vergence movements; for an overview see Holmqvist et al., 2011 and Land, 2011).

instruction (e.g., Thomas & Lleras, 2009), or be undertaken to widen the field of view, e.g., while driving (e.g., Castro, 2009). Rich empirical evidence however suggests that before the eye is moved, attention shifts to the upcoming saccadic landing point (e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995). Furthermore, eye movements and attention share the same neural resources (Kristjánsson, 2011). Holmqvist et al. (2011) suggest therefore that the relation between eye fixations and cognitive processing can be described as an analogy to a rubber band. Stretching the rubber band to one point (the point of cognitive processing) means the other end of the rubber band (the eye fixations) will naturally follow. Thus, the fixation location and the duration a location is fixated can be used as an approximation of what information is actually being processed. Nevertheless, eye movements capture cognitive processes only indirectly and skillful experimental manipulation is warranted to draw valid conclusions (Holmqvist et al., 2011).

The tight coupling of eye movements and cognitive processing are just one factor leading to eye movements becoming a popular topic of study in cognitive science. Another factor is due to measuring equipment becoming more reliable and effective in the last decades (Holmqvist et al., 2011). By combining video recordings of the pupil with the cornea-reflection (recorded with an infrared light) eye and head-movements can be separated (see Figure 1.1 as an example of an eye-tracking system using the cornea-reflection method). This allows for the monitoring of eye movements while people look at real or virtual visual displays. Furthermore, because people are free to move, it also allows for the studying of eye movements whilst a viewer interacts with presented objects (Henderson & Ferreira, 2004). These possibilities have prompted a significant increase in eye movement studies, with the topic having been intensively studied in relation to reading, scene perception and visual search (see Rayner, 2009 for an overview). Eye movements have not only been used to study cognitive processing in such visual tasks, but they have also been studied in the context of spoken language comprehension, in which eye movements are recorded whilst people listened to spoken information and watched visual objects on a screen (Henderson & Ferreira, 2004; Huettig, Olivers, & Hartsuiker, 2011; Liversedge & Findlay, 2000). Research in this particular field concluded that during the processing of temporarily ambiguous linguistic input, eye movements revealed developing and changing interpretations (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). Eye movements can also be reliably directed towards visible objects and characters mentioned in speech (e.g., Allopenna, Magnuson, & Tanenhaus, 1998). Altmann and Kamide (2007) showed that participants looked at the locations at which objects had previously been

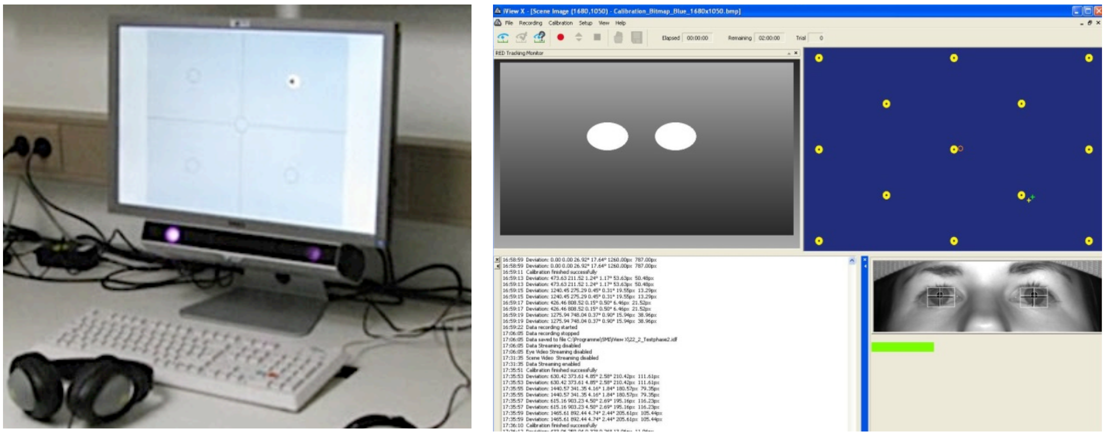

Figure 1.1 Left: Eye tracker setup of a remote eye tracker (SMI, Teltow) as used in the studies reported in this thesis. Auditory materials were presented via headphones. **Right:** Data collection performed by the iViewX software (SMI, Teltow). The picture displays parameters of eye tracking quality. From top left to bottom right: RED tracking monitor, the result of a validity test, system logger data, and eye image.

present on a computer screen at the moment the objects were mentioned in a spoken sentence. They further demonstrated that the eyes move towards object locations that are likely to be mentioned next during the unfolding of a spoken sentence (Altmann & Kamide, 2009).

1.1.2 Looking-at-nothing Phenomenon

Eye movements are not only directed towards objects present in the visual environment; they can also be directed to objects no longer present. Language-induced eye movements are for example directed to objects that have been present, but which are no longer present at the time they are retrieved from memory. In such studies, participants look at a blank screen when retrieving information during memory retrieval. This eye movement behaviour is said to be top-down driven (Henderson, 2007; Johansson, 2013; Spivey & Dale, 2011). Among the first to show a close link between eye movements, linguistic information processing, and spatial information processing in an information-retrieval task were Richardson and Spivey (2000). They presented participants with a spinning cross (Experiment 2) in one of four equal-sized areas on a computer screen, together with spoken factual information. After four facts were presented, participants heard a statement testing one of the presented sentences and were asked to judge the truth of the statement. Even though the computer screen remained blank during this retrieval phase, participants fixated more often in the spatial area where the sought-after information had been presented (relevant area) compared to the other three areas on the screen (irrelevant areas).

Since this first empirical investigation, a growing empirical source of evidence has demonstrated the existence of the so-called “looking-at-nothing” phenomenon in a variety of situations (Altmann, 2004; Brandt & Stark, 1997; Jahn & Braatz, 2014; Johansson, Holsanova, Dewhurst, & Holmqvist, 2012; Johansson et al., 2006; Laeng, Bloem, D'Ascenzo, & Tommasi, 2014; Laeng & Teodorescu, 2002; Martarelli & Mast, 2010, 2013; Platzer, Bröder, & Heck, 2014; Renkewitz & Jahn, 2012; Spivey & Geng, 2001). Studies using visuospatial information presented participants with information in a visual array, for instance, shape and color of symbols (Spivey & Geng, 2001), different kinds of tropical fish (Laeng & Teodorescu, 2002) or rich visual scenery (Johansson et al., 2006), and later probed participants on the visualized information whilst the screen was blank. Studies employing verbal information presented participants with abstract symbols, as demonstrated in the study by Richardson and Spivey (2000), or alternatively as carried out in the work of Johansson et al. (2012), participants were confronted with an empty screen while they listened to a statement or description. During a subsequent retrieval phase, memory of the verbal material was tested. Interestingly in these situations, eye movements reflect content and spatial relations of a mental image built during the auditory description of the scenery.

The above described scenario is based on a remembered event that takes place immediately prior to retrieval. Spatial indexing of multimodal events can however also take place during long-term episodic memory retrieval, where a set of information is first learned by heart and tested during subsequent trials – even one week following the learning (Jahn & Braatz, 2014; Laeng et al., 2014; Martarelli & Mast, 2013). This ability does not reflect a temporarily stored event, but on the contrary, it means that episodes are stored in the long-term memory whilst demonstrating the robust and durable nature of eye movements to nothing (Spivey, 2007). Furthermore spatial indexing also occurs during mental imagery of auditorily presented information (Johansson et al., 2006), where no visual reference frames have been presented during a preceding encoding phase. There are consequently multiple scenarios in which spatial indexing of memorized information occurs (Jahn & Braatz, 2014).

What are the mechanisms underlying looking-at-nothing? Most authors agree on the assumption that looking-at-nothing reflects retrieval from a multimodal memory representation (Figure 1.2) that is built during the encoding of information from the environment. More precisely, during encoding, input from multiple modalities (e.g., visual, auditory) is stored in an episodic trace (Altmann & Kamide, 2007, 2009; Altmann, 2004; Hommel, 1998, 2004) in working memory (Baddeley & Hitch, 1974; Baddeley, 2000), together with conceptual knowledge derived from long-term memory (e.g., Huettig et al., 2011).

The activation however of a multimodal memory representation alone is not sufficient to cause eye movements to revert back towards associated spatial locations. Some sort of spatial pointer (Ballard et al., 1997; Henderson, 2003) or index (Altmann & Kamide, 2009; Pylyshyn, 2001; Richardson, Dale, & Kirkham, 2007) is required to trigger gaze behaviour. Spatial indexing demands that the location of information presentation is encoded together with the multimodal memory representation (Hoover & Richardson, 2008; Richardson & Kirkham, 2004; Spivey & Dale, 2011). The spatial index is rather based on spatiotemporal

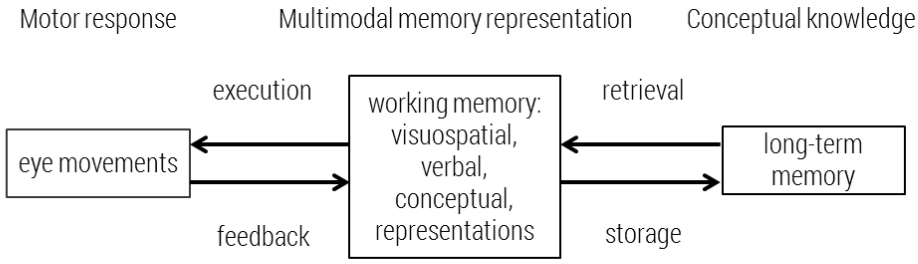

Figure 1.2 Framework of a multimodal memory representation, its interaction with long-term memory and the execution of eye movements.

constraints rather than object features (Hoover & Richardson, 2008; Jahn & Braatz, 2014). The activation of an episodic trace spreads to and activates the motor system, triggering the execution of an eye movement that is prepared in the linked spatial index (Spivey & Dale, 2011). The stronger the association in the multimodal memory representation, the higher "the probability of triggering a saccadic eye-movement" (Huettig et al., 2011, p. 5).

1.2 Thinking and Memory

Holyoak and Morrison (2012) describe thinking as: "systematic transformation of mental representations of knowledge to characterize actual or possible states of the world, often in service of goals" (p. 1). From this perspective, we have some internal description that can be manipulated in order to form other descriptions. These manipulations are systematic. The internal descriptions created by thinking describe states of the external world (e.g., a constructed image of the room you are in) and they are directed to achieving some desired state of affairs that motivate the thinker to carry out mental work (e.g., sitting down at your office chair). Furthermore, thinking summarizes cognitive processes involved in planning, remembering, conceptualizing, decision-making, and reasoning (Holyoak & Morrison, 2012).

1.2.1 Thinking Processes and Mental Representations

Describing how mental representations interact with cognitive processes involved in perceiving and storing information has received more and more attention in order to explain thinking (e.g., Manktelow, 2012 writes in his introduction of his book on thinking and reasoning: "Explaining reasoning: the 'new paradigm' ", p. vii, see also Markman, 2012).

Evans (2012) gives two reasons for this development: Firstly, numerous examples have been encountered were humans deviate from purely logical or rational predictions. For example, in the Wason-Selection Task (Wason, 1966), participants had to decide which of four cards they would choose in order to test the truth of a sentence. Participants could see on the visible side of the cards either a “D”, a “K”, a “3”, or a “7”. They were then informed that: “If there is a D on one side, then there is a 3 on the other side”. A significant number of participants selected the D card (modus ponens), however a large proportion of participants also chose the 3 card, which constitutes a confirmation of the consequent, opposed to the selection of the card featuring the number 7 (modus tollens) (Oaksford & Chater, 1994). By selecting in this manner, participants in this task did not behave according to logical norms.

Secondly, it has been found that the outcome of a thinking process depends on the content of the task. This is epitomized in the Selection Task, in which people are less likely to confirm the consequent if the task is framed as violating a regulation (e.g., “If a letter is sealed, then it has a 50c stamp on it”; Johnson-Laird, Legrenzi, & Legrenzi, 1972). One explanation for content effects lies in the assumption that different contents engage different kinds of reasoning, i.e. true/ false judgments versus reasoning about regulations (Manktelow, 2012). This means that from a logical point of view identical tasks that only differ in their framing result in different outcomes. Theories that therefore aim to explain thinking processes must include differences in cognitive processes elicited by different contents.

Another reason why it is potentially interesting to investigate the nature of mental representations underlying thinking is the assumption that cognition can be better understood if studied in the context of its relationship to a physical body that interacts with the world, i.e. from a grounded perspective on cognition (Barsalou, Kyle Simmons, Barbey, & Wilson, 2003; Barsalou, 2008; Spivey & Dale, 2011; Spivey, 2007; Wilson, 2002). Grounding cognition in space and time comprises several approaches: (1) The situated perspective on cognition assumes that during cognitive processing, perceptual information is continuously drawn upon and affects processing, and motor activity is executed that affects the environment in a task-relevant way (Wilson, 2002); (2) Cognition comprises mental simulations. This means the “reenactment of perceptual, motor, and introspective states acquired during experience with the world, body, or mind” (Barsalou, 2008, p. 618); (3) The embodiment of cognition approach sees cognitive processes as directly involving modal sensorimotor systems, for instance, visual, somatosensory, and auditory perception, as well as oculomotor and skeletomotor planning (Spivey & Dale, 2011). All approaches share the assumption that cognitive processing is not independent from modal representations. Theories that therefore aim to explain thinking processes should therefore incorporate sensorimotor and modal representations held in memory.

1.2.2 Memory-based Reasoning and Decision-Making

Many of our everyday thinking activities draw upon information that is currently absent from the world, and hence has to be retrieved from memory. An example of such is the situation in which a medicine is chosen to treat a likely explanation for a set of observed symptoms from memory (Johnson & Krems, 2001). Research on sequential diagnostic reasoning has shown that inferences drawn from memory elicit different cognitive processes than inferences based on on-line available information. For example, when studying memory-based reasoning processes, the order in which information is presented during sequential diagnostic reasoning changes the explanation status of hypotheses held in memory (Baumann, Krems, & Ritter, 2010; Rebitschek, Scholz, Bocklisch, Krems, & Jahn, 2012). Moreover, the set of contending hypotheses depends on the availability of information in working memory (Mehlhorn, Taatgen, Lebiere, & Krems, 2011).

Research on judgment and decision-making has shown that inferences from memory, in comparison to inferences from givens, induce selective and heuristic processing (Gigerenzer & Goldstein, 1996; Gigerenzer, Todd, & the ABC research group, 1999), and result in less compensatory strategy use (Bröder & Schiffer, 2003, 2006), more sequential memory-search (Bröder & Gaissmaier, 2007) and more recognition-based decision-making (Pachur, Bröder, & Marewski, 2008). A strategy that recently received a considerable amount of attention in the field of decision-making is the similarity-based decision strategy. Similarity-based decision strategies assume that in order to decide between alternatives, each option is compared to past instances stored in memory (Bröder, Newell, & Platzer, 2010; Hahn & Chater, 1998; Hahn, Prat-Sala, Pothos, & Brumby, 2010; Juslin & Persson, 2002). Whereas recent findings assume that people use a trade-off between accuracy and effort in order to decide when to use a similarity-based strategy (Hoffmann, von Helversen, & Rieskamp, 2013, 2014; Hoffmann, 2014), the underlying cognitive processes remain difficult to tease apart (Ashby & O'Brien, 2005; Barsalou, 1990; Hahn & Chater, 1998; Markman et al., 2005; Pothos, 2005).

To sum up, in order to understand thinking behaviour involved in reasoning and decision-making, it is essential to study memory processes (Bröder & Schiffer, 2003; Bröder, 2005; Gigerenzer et al., 1999; Renkewitz & Jahn, 2012), or as Weber and Johnson (2009) state: "the brain that decides how to invest pension money and what car to buy is the same brain that also learns to recognize and categorize sounds and faces, resolves perceptual conflicts, acquires motor skills such as those used in playing tennis, and remembers (or fails to remember) episodic and semantic information." (p. 54).

1.3 Eye Movements and Thinking

To track cognitive processes, proper process measures are required (Johnson, Schulte-Mecklenbeck, & Willemsen, 2008; Schulte-Mecklenbeck, Kühberger, & Ranyard, 2011). Eye movements are one such measure that can be used to trace cognitive processes underlying thinking (Glaholt & Reingold, 2011; Orquin & Mueller Loose, 2013; Peterson & Beck, 2011), because oculomotor processing is assumed to be coextensive with cognitive processing (Spivey & Dale, 2011). That is, during thinking, the brain recruits low-level sensorimotor neural subsystems, like eye movements, to assist in cognitive computations. For example, in the domain of problem solving it has been shown that eye movements are informative about the encoding superiority assumed in chess experts. Expert chess players make fewer fixations than novices and place fixations in between individual pieces on a chess board (Reingold & Sheridan, 2011). In a study testing Duncker's radiation problem, Grant & Spivey (2003) found that participants that solved the task spent more time looking at the stomach-lining portion of the diagram than unsuccessful solvers (see also Thomas & Lleras, 2007, 2009).

1.3.1 Eye Movements and Decision-Making

Eye movements have also been studied in the domain of decision-making, ranging from perceptual decisions of which stimulus to gaze at next (Ludwig, 2011), to principles of decision-making that apply to more complex decision problems (Glaholt & Reingold, 2011; Orquin & Mueller Loose, 2013), like deciding which of two cities is larger, who will win the next elections, or consumer choices (Gigerenzer & Gaissmaier, 2011). Concerning more complex decisions, eye movements have been shown to be a useful tool to explore the underlying processes. For example, alternatives that are fixated first and last have a higher probability of being chosen, as these have more accumulated evidence. The more similar alternatives, the more information is sampled, leading to longer gaze durations for these alternatives and the favored alternative (for an overview see Orquin & Mueller Loose, 2013).

Most of these results have been obtained by studying decision-making when information was visible or could be collected by turning cards or clicking on information (Glaholt & Reingold, 2011). The information required therefore had not been recalled from memory. Evidence is accumulating however that cognitive processes involved in inferences from givens differ from inferences drawn from memory (Bröder & Gaissmaier, 2007; Bröder & Schiffer, 2003, 2006; Pachur et al., 2008; Platzer & Bröder, 2012, 2013). Until recently, it was thought to be not possible to study memory-processes involved in decision-making. To make memory-based decision processes visible and the study of them more viable, Renkewitz and Jahn (2010, 2012) developed a process tracing method called memory indexing (see also Scholz, 2011).

Memory indexing is based on the looking-at-nothing phenomenon and thus utilizes the human ability to spatially index multimodal events. In the memory indexing experiment by Renkewitz and Jahn (2012), participants first learned information concerning six decision alternatives (fictive mushrooms). Alternatives were described by four cue values (e.g., elastic consistency, cell wall consists of cellulose, contains magnesium as mineral, and rare spread). In a learning phase, the mushrooms were repeatedly presented as abstract geometrical forms. Cue values were written in rectangles placed within the geometrical forms. After completion of the learning phase, participants were told which cue values indicated poisonous and how cue dimensions were ordered in terms of validity. During subsequent test trials, participants were presented with binary decision problems in which they had to indicate which of two mushrooms were more poisonous. In each decision trial therefore two of the six mushrooms were presented next to each other. Importantly, in order to study memory-based decisions, the rectangular frames containing cue values during the learning phase were empty. Eye movements were recorded throughout the decision phase. Furthermore, there were two decision phases; in phase 1 participants spontaneously adopted a decision strategy, and in phase 2, they were instructed to either use the compensatory equal-weights strategy, or the non-compensatory take-the-best strategy (as outlined in Gigerenzer & Gaissmaier, 2011). The take the best approach is termed a non-compensatory strategy because cues that are lower in validity are disregarded. Disregarded cues cannot compensate for differences in other cue values. Equal weights is recognized as a compensatory strategy because it takes all cue values into account but ignores their validity. Non-compensatory strategies are associated with a more cue-wise information search, whereas compensatory strategies are associated with alternative-wise information search (see Renkewitz & Jahn, 2012).

Both transitions between alternatives, in addition to looking times at rectangular frames containing cue values during learning, revealed cue-wise information search for users of a non-compensatory strategy, and alternative-wise information search when applying a compensatory decision strategy. These findings provided the first evidence that eye movements can indeed be studied to trace memory processes during decision-making, in which information was based on linguistic input and cue values had to be retrieved from long-term memory.

1.3.2 Eye Movements and Reasoning

Eye movements have also been used to investigate reasoning. In relational spatial reasoning, for instance, more vertical than horizontal eye movements are shown when solving a below/above inference problem (Demarais & Cohen, 1998). This especially occurs when participants are sitting in front of an empty screen. Eye movements thus generate some form of spatial mental model to assist with logical induction (Byrne & Johnson-Laird, 1989), and eye movements are performed that are consistent with the spatial characteristics of that mental model (Spivey & Dale, 2011). Hegarty (2004) showed that during mechanical reasoning about movements of ropes in a pulley system, participants mentally animated small portions of the pulley system in sequential order, reflecting the causal chain of forces.

Eye movements also function as a tool to investigate memory-based reasoning processes (Jahn & Braatz, 2012, 2014; Ruthsatz, 2009). In the study conducted by Ruthsatz (2009), participants first learned cue information concerning four flatmates. Each flatmate was described by two cues (for example flatmate A smokes and likes reading novels). Cues were either uniquely associated with one flatmate or alternatively shared by two flatmates, and were thus ambiguous (e.g., flatmate A and B smoke, whereas flatmate A likes reading and flatmate B likes playing computer games). In a preceding learning phase, participants learned the cue information relating to each of the four flatmates. An abstract symbol of a head appeared in one of four spatial areas on a computer screen whilst simultaneously an auditory description of the cues was played. The four spatial areas were through this process individually associated with each of the four flatmates. During a subsequent reasoning phase, in which participants were shown the four empty spatial areas on the computer screen, participants were sequentially presented with the cues and had to infer which flatmate remained last in the common room of the flat. For example, participants heard the cue information cigarettes (flatmate A or flatmate B) and book (flatmate A); in this case, flatmate A was the last person to remain in the common room. There was always a single correct explanation, and in order to control for gaze biases, each of the four flatmates could have assumed the A-role. Eye movements were recorded throughout the reasoning phase.

In order to test if eye movements can reveal memory processes in diagnostic reasoning throughout the sequence of sequentially presented cues, the author of this paper has reanalyzed the data by Ruthsatz (2009) (see Scholz, Mehlhorn, & Krems, 2011; Scholz, Mehlhorn, Ruthsatz, & Krems, 2011). Figure 1.3 shows results of 40 participants on fixation proportions based on the number of fixations for two cue sequences and only correct responses. Gaze pattern reflected the support that each flatmate received through the sequence of presented symptoms. When an ab symptom was presented, participants gazed more to flatmates A and B than to flatmates C and D. When an A-symptom was presented, participants gazed more often to flatmate A than to any other flatmate. When giving the response, participants gazed to the explanation they finally chose. Results of this pre-study showed that eye movements indeed reveal memory-based diagnostic reasoning of sequentially presented symptoms over time.

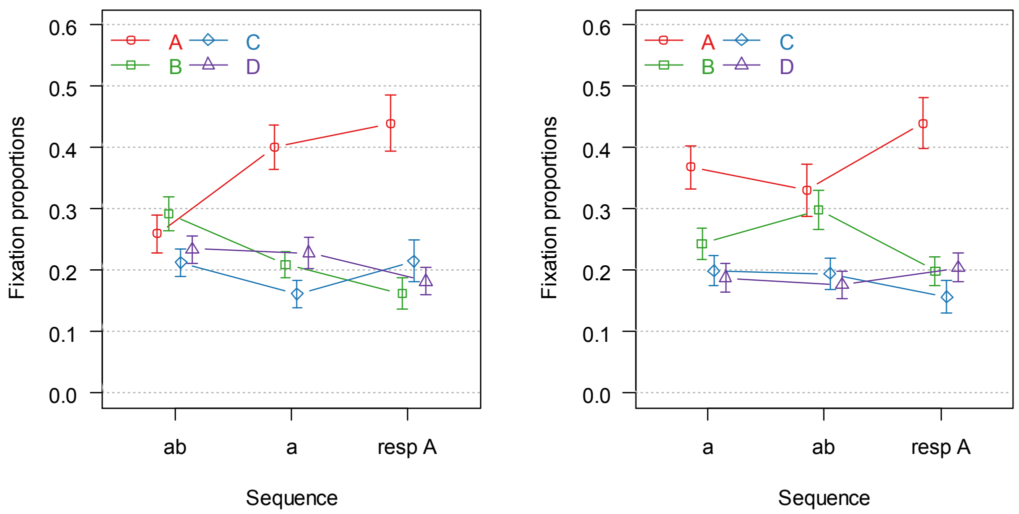

Figure 1.3 Mean fixation proportions for the ab-a-response and a-ab-response sequences and the four spatial areas (A, B, C, and D). Error bars show standard errors of the mean.

Jahn and Braatz (2012; 2014) investigated gaze behaviour in sequential diagnostic reasoning with sequences consisting of four cues (henceforth called “symptoms”). Participants were told to imagine they were physicians identifying a chemical with which a worker in a chemical plant was affected during an accident (“chemical-accident task”, Mehlhorn et al., 2011). Information about chemicals, their respective symptom classes, and the symptoms they caused were learned during a preceding learning phase, for instance, the category “eyes” consisted of symptoms “eyelid swelling” and “lacrimation”. Categories of symptoms were associated to spatial locations and chemicals (hypotheses). During reasoning trials, symptoms were presented auditorily in sequence. Memory indexing showed the activation status of hypotheses in memory over the course of a reasoning trial (Jahn & Braatz, 2014): At the beginning of a trial, eye movements matched the momentary probabilities of hypotheses given their differential support by the first symptom. During subsequent symptom presentations, eye movements reflected the changing subjective probabilities of competing hypotheses corresponding to the combined support that they received from symptoms presented so far in the experiment (integrated probability matching). In the study by Jahn and Braatz (2014), in most sequences a single final diagnosis was left outstanding until all symptom information had been presented.

1.4 Overview and research objectives

Recent research has outlined the tight coupling of eye movements and memory processes. However, this research mainly focussed on the relation between eye movements and visuospatial information processing. Evidence for a tight coupling of eye movements for the processing of verbal information is scarce. Understanding the relation between eye movements and memory retrieval for verbal information constitutes a precondition for using eye movements as a direct behavioural correlate to explore complex thinking processes by showing that the same set of mechanisms is operating when critical information is verbal in nature. Therefore, the first part of the thesis focuses on the relation between eye movements and memory retrieval for verbal information. The second part of this thesis uses eye movements, i.e. the looking-at-nothing phenomenon, to study memory processes involved in rule- and similarity-based decision-making and sequential diagnostic reasoning of ambiguous symptom sequences. In the following research objectives are outlined. More precise hypotheses are included in Chapters 2 to 5.

1.4.1 Chapter 2: Functional Spatial Indexing of Verbal Information

If motor patterns, like eye movements, feedback information into the cognitive system during memory retrieval, one could assume that eye movements improve memory retrieval for an object or event. Although research testing visuospatial materials and manipulating eye movements as an independent variable initially showed evidence for such a functional role of eye movements for memory retrieval (Johansson & Johansson, 2014; Laeng et al., 2014), the results however in relation to verbal materials are not conclusive (Hoover & Richardson, 2008; Richardson et al., 2009; Richardson & Kirkham, 2004; Richardson & Spivey, 2000).

Research objective 1: Are eye movements to nothing functional for memory retrieval of verbal information?

A series of three experiments were conducted using a similar methodology and all concluded with the same pattern of results (see Scholz & Krems, 2011; Scholz, Mehlhorn, & Krems, 2012a, 2012b). The study reported in Chapter 2 will only report the last experiment in the series that incorporates all tested manipulations. Lars Eberspach assisted in the programming involved in the experiment and collected parts of the data (Eberspach, 2013). Chapter 2 is based on a published manuscript (Scholz, Mehlhorn, & Krems, 2014).

1.4.2 Chapter 3: Looking-at-nothing and Practice

This chapter aims at further exploring the relation between eye movements and memory retrieval for verbal information. It questions whether looking-at-nothing is an automatic behaviour that always occurs when verbal information that is associated with a spatial location is probed. Alternatively, looking-at-nothing behaviour could change, for example with varying degrees of strengths of the information held in memory.

Research objective 2: Are eye movements automatically launched to spatial locations? More precisely, is looking-at-nothing behaviour stable under different levels of practice?

The experiment reported in Chapter 3 explored looking-at-nothing behaviour and manipulating the degree of practice in a task, where auditory information, which is associated with contents from a visual scene, has to be retrieved from memory. Chapter 3 is based on a published conference proceeding (Scholz, Mehlhorn, Bocklisch, & Krems, 2011).

1.4.3 Chapter 4: Access of Information from Multimodal Memory Representations

Eye movements reflect information processing from memory. Can eye movements be studied in order to disentangle decision strategies on the process level? For example, to investigate when previous experiences stored in memory are retrieved and when they are not retrieved? This is epitomized in the following example; in order to find a correct explanation for a patient's symptom, a medicine could be selected on the terms of either similar instances stored in memory or its selection could be derived from an abstract rule. There has been an extensive and long lasting debate concerning the differences in cognitive processes between such similarity-based and rule-based decision strategies. Recently it has been assumed that both strategies draw on retrieval from a mental representation, but differ in the way in which information is accessed from memory (Bailey, 2005).

Research objective 3: Can eye movements be used as a direct behavioural correlate to study differences in memory retrieval between a rule- versus a similarity-based decision strategy?

The two experiments reported in Chapter 4 used memory indexing to study retrieval processes involved in similarity- and rule-based decision-making. Bettina von Helversen and Jörg Rieskamp advised in the study design and in conducting the experiments. Chapter 4 is based on a published manuscript (Scholz, von Helversen, & Rieskamp, 2015).

1.4.4 Chapter 5: Eye Movements and the Development of Explanations over Time

Eye movement recordings have been shown to provide continuous data about ongoing memory processes. For instance, by observing eye movements throughout the sequential presentation of symptoms, the activation status of different explanations in memory can be observed (Jahn & Braatz, 2014).

Research objective 4: Can eye movements track the development of hypothesis over time, i.e. from the first symptom presentation until the participants' response, especially in situations where the presented evidence is ambiguous, thus supports more then one hypothesis?

In order to clarify this, one experiment has been conducted. Ricarda Fröde assisted in the generating of materials used in this experiment and was involved in data collection (Fröde, 2012). Georg Jahn advised on study design and provided valuable feedback on the manuscript presented in Chapter 5.

2 Functional Spatial Indexing of Verbal Information

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2.1 Abstract

People fixate on blank spaces if visual stimuli previously occupied these regions of space. This so-called "looking-at-nothing" phenomenon is said to be a part of information retrieval from internal memory representations, but the exact nature of the relationship between looking-at-nothing and memory retrieval is unclear. While evidence exists for an influence of looking-at-nothing on memory retrieval for visuospatial stimuli, evidence for verbal information is mixed. Here, we tested the relationship between looking-at-nothing behaviour and memory retrieval in an episodic retrieval task where verbal information was presented auditorily during encoding. When participants were allowed to gaze freely during subsequent memory retrieval, looking-at-nothing occurred, and it was stronger for correct than for incorrect responses. When eye movements were manipulated during memory retrieval, retrieval performance was higher when participants fixated on the area associated with to-be-retrieved information than when fixating on another area. Our results provide evidence for a functional relationship between looking-at-nothing and memory retrieval that extends to verbal information.

Keywords: verbal memory retrieval, eye movements, looking-at-nothing, spatial indexing, event file, encoding-retrieval relationship, situated cognition

2.2 Introduction

While there is compelling evidence that eye movements are engaged in cognitive tasks like reading, scene perception and visual search (Rayner, 2009), eye movements also occur when the outside world is devoid of any task-relevant information. Coining the term "looking-at-nothing" (LAN) phenomenon, Richardson and colleagues (Hoover & Richardson, 2008; Richardson & Kirkham, 2004; Richardson & Spivey, 2000) have shown that the retrieval of verbal information from memory leads the gaze back to spatial locations that were previously associated with the retrieved information. Similar memory-driven eye movement behaviour during retrieval of past events has been shown in the context of language processing (Altmann, 2004), mental imagery (Brandt & Stark, 1997; Johansson et al., 2012, 2006; Laeng et al., 2014; Laeng & Teodorescu, 2002; Martarelli & Mast, 2010, 2013; Spivey & Geng, 2001), and reasoning and decision-making (Jahn & Braatz, 2014; Platzer et al., 2014; Renkewitz & Jahn, 2012; Scholz, von Helversen, & Rieskamp, 2015).

Recently, a discussion has emerged as to whether such eye movements during memory retrieval are purely an epiphenomenon or whether they play a functional role in the retrieval of information from memory (Ferreira et al., 2008; Richardson et al., 2009). That is, does returning the eyes to a spatial location, which is associated with the to-be-retrieved information, facilitate the retrieval of this information from memory? Indeed, it is possible that eye movements are functionally related to memory performance. The chain of events might occur as follows: While encoding of information from the environment, eye movements are stored as part of an episodic memory representation (in the form of a spatial index, Pylyshyn, 2001; Richardson & Kirkham, 2004). Retrieving parts of the episodic trace, for instance, by probing for parts of the stored information, leads to the execution of the spatial index that elicits an eye movement to the location where a visual object was presented during encoding (Altmann & Kamide, 2007, 2009; Anderson, Chiu, Huette, & Spivey, 2011; Hoover & Richardson, 2008; Jahn & Braatz, 2014; Laeng et al., 2014; Laeng & Teodorescu, 2002; Renkewitz & Jahn, 2012; Richardson & Kirkham, 2004 for overviews see Ferreira et al., 2008; Huettig, Mishra, & Olivers, 2012; Huettig et al., 2011; Richardson et al., 2009). The binding of information in an episodic trace is not limited to object-related features, but applies to action planning and sensorimotor processing (Hommel, 1998, 2004), i.e. the execution of an eye movement generated in the linked spatial index (Hoover & Richardson, 2008; Spivey & Dale, 2011). In recreating this eye movement, memory activation for other associated information increases (Altmann & Kamide, 2007; Huettig et al., 2011; Mayberry, Crocker, & Knoeferle, 2009), and therefore increases the chance of successfully retrieving the probed information (Johansson et al., 2012; Johansson & Johansson, 2014; Laeng et al., 2014; Laeng & Teodorescu, 2002).

Enhanced memory performance by reenacting processes that were engaged at encoding is consistent with the principles of "encoding-specifity" (Tulving & Thomson, 1973; Tulving, 1983) and "transfer appropriate processing" (Morris, Bransford, & Franks, 1977), that state that memory performance is a function of the degree to which cognitive operations engaged at encoding are reenacted at retrieval (see also Foulsham & Kingstone, 2013; Holm & Mäntylä, 2007; Mäntylä & Holm, 2006). Furthermore, it is in line with accumulating evidence demonstrating that retrieval activates the same brain regions that were active during encoding (for an overview see Danker & Anderson, 2010; Kent & Lamberts, 2008; Rugg, Johnson, Park, & Uncapher, 2008; Rugg & Wilding, 2000). Taken together, eye movements to empty spatial locations should be functional in the retrieval of both visuospatial and verbal information from memory.

Previous studies looking at looking-at-nothing during retrieval of verbal information have reported null results on the relation between eye movements and memory performance (Hoover & Richardson, 2008; Richardson & Kirkham, 2004; Richardson & Spivey, 2000). In the classic looking-at-nothing study, Richardson and Spivey (2000) auditorily presented participants with semantic statements, which were only loosely associated with a spatial location on a screen through a visual cue. For example, participants heard the sentence "Claire gave up her tennis career, when she injured her shoulder" while a spinning cross was presented in one of four areas of the screen (henceforth called the "relevant area"). Subsequently, the screen went blank and participants answered a question about one of the presented statements. Participants exhibited LAN, that is, they tended to look back to the relevant area during the retrieval phase, even though the to-be-recalled information had been presented auditorily and the visual cue was not relevant to the task (Hoover & Richardson, 2008; Jahn & Braatz, 2014; Laeng et al., 2014). Richardson and Spivey (2000) compared participants' response accuracy between trials with at least one fixation on the relevant area (which they defined as "LAN trials"), to trials with no fixations on this area ("no LAN" trials). They found no significant difference between the trials. In a similar study also testing verbal memory retrieval, Hoover and Richardson (2008) correlated gaze duration on relevant spatial locations with response accuracy. Again, they found no effect.

There is evidence of a functional relationship between eye movements and memory from studies testing visuospatial material (Johansson et al., 2012; Johansson & Johansson, 2014; Laeng et al., 2014; Laeng & Teodorescu, 2002; Martarelli & Mast, 2010). The general procedure in these studies was to first associate visuospatial information (e.g., characteristics of a tropical fish, see Laeng & Teodorescu, 2002) with distinct spatial locations during a preceding encoding phase. During a subsequent retrieval phase, the screen is blank and participants are instructed to retrieve the previously encoded information (e.g., the fish's color or orientation in space, see Laeng & Teodorescu, 2002). By analyzing participants' spontaneous gaze behaviour during memory retrieval, Martarelli and Mast (2010) showed that children gazed more often at the location they were viewing while the respective information was encoded when answering correctly than when answering incorrectly. Some studies induced an eye movement manipulation, i.e. manipulated eye movements as an independent variable, in order to clarify the relation between eye movements and memory retrieval (Johansson et al., 2012; Johansson & Johansson, 2014; Laeng et al., 2014; Laeng & Teodorescu, 2002). For example, Johansson and Johansson (2014) asked participants to recall information about previously encountered objects while fixating on either an area associated with the to-be-recalled information (congruent) or while fixating on another area (incongruent). They found impaired retrieval performance when participants fixated on the incongruent area compared to when they fixated on the congruent area. Additionally, participants' response times were longer when fixating on the incongruent compared to the congruent area. Taken together, these studies provide converging evidence that eye movements indeed play a functional role in memory retrieval of visuospatial information.

Can we, therefore, conclude that a functional relationship between eye movements and memory retrieval is restricted to the retrieval of visuospatial information and does not extend to the retrieval of verbal information? No, because the available evidence on the functional relationship between looking-at-nothing and the retrieval of verbal information from memory is inconclusive for several reasons. First, measures that have been used to investigate the relationship in studies with verbal material (e.g., comparison between one-fixation and no-fixation trials) are not very sensitive: A single fixation in the relevant area could easily be caused by random gaze behaviour. Second, the analyses of the relation between eye movements and memory retrieval by Richardson and colleagues were correlational, and thus, do not allow for a causal conclusion, because they did not experimentally manipulate gaze behaviour. Therefore, Richardson et al. (2009) call for a stronger test of a possible functional relationship between looking-at-nothing and verbal memory retrieval: "Until evidence is reported where eye movements are manipulated as an independent variable, and memory for linguistic information is affected, we choose to remain agnostic." (p. 235). Third, research findings from related fields suggest an interaction between visuospatial and verbal components of an episodic memory representation. For example, studies of spoken language comprehension found that object fixation can change the interpretation of spoken language (Allopenna et al., 1998; Tanenhaus et al., 1995 for an overview see Anderson & Spivey, 2009). These findings indicate a strong coupling between eye movements and verbal information processing, which is consistent with a grounded perspective on cognition (Barsalou et al., 2003; Barsalou, 2008; Kent & Lamberts, 2008; Spivey, 2007; Wilson, 2002). Therefore, the findings suggest that the relationship between gaze behaviour and memory retrieval might also extend to the retrieval of verbal information.

The goal of the current study is to clarify the relationship between gaze behaviour and the retrieval of verbal information from memory. To do so, we use a variation of the original looking-at-nothing paradigm (Richardson & Spivey, 2000) in which memory of verbal information is tested by presenting auditory statements that are only loosely associated with a spatial location via a task-irrelevant visual cue. In order to clarify the relation between gaze behaviour and verbal information retrieval performance, we test the relation in two different, but complementary, ways. During a first block of trials, effects of looking-at-nothing on retrieval performance are assessed under a free gaze condition (i.e. participants are allowed to gaze freely) by comparing looking-at-nothing trials with correct responses to those with incorrect responses. We hypothesize that if eye movements are related to the retrieval of associated verbal information, looking-at-nothing should be stronger during retrievals that result in correct responses than during retrievals that result in incorrect responses. A second block tests the effects of a gaze manipulation on retrieval performance, by comparing retrieval performance on trials where a spatial cue is shown in an area associated with the to-be-recalled information (congruent) to trials where such a cue is shown in another area, i.e. adjacent or diagonal areas (incongruent). If eye movements are related to the retrieval of associated verbal information, response accuracy should be higher in the congruent than in any of the incongruent conditions. Furthermore, if the gaze manipulation affects the availability of information held in memory, response times should be shorter in the congruent compared to the incongruent conditions.

2.3 Method

2.3.1 Participants

Twenty-eight native German speaking students from Technische Universität Chemnitz participated in the experiment (22 female, mean age 23.4 years, ranging from 19-39). All had normal or corrected to normal vision.

2.3.2 Apparatus

Participants were seated at a distance of 630 mm in front of a 22'' computer screen (1680 x 1050 pixels) with their head in a chin rest. Stimuli were presented with E-Prime 2.0 running on a separate computer. An SMI iView RED eye tracker sampled data from the right eye at 120Hz with a precision of 0.05° that were recorded with iView X 2.5 following 5-point calibration. Data were analyzed with BeGaze 2.3. Fixation detection had a dispersion threshold of 100 pixels and a duration threshold of 100 ms (cf. Richardson & Spivey, 2000).

2.3.3 Material

Visual stimuli in the encoding phase consisted of a grid dividing the screen into four equal-sized spatial areas (Figure 2.1) and four black circles in the center of each spatial area. To associate spatial areas with the auditory stimuli, a symbol of a loudspeaker appeared in the circle of the respective area. During retrieval phases in the free gaze condition, participants saw the grid and circles only. During the retrieval phases in the gaze manipulation conditions, we manipulated gaze behaviour with a spatial cue (cf. Mulckhuyse & Theeuwes, 2010;

Theeuwes, 2010; Yantis & Jonides, 1981). The spatial cue was a red dot, blinking at 2 Hz that appeared in one of the four circles in the center of each spatial area.

Auditory stimuli during encoding consisted of 28 sentences. Each sentence was comprised of a name and four attributes describing an artificial city (e.g., “In Velbert you can find a bicycle museum, a sickle-shaped bay, a red lighthouse and an inland port.”). City names were randomly selected small cities from an online resource for German postcodes (http://www.postdirekt.de/plzserver/). Attributes consisted of buildings, institutions, sights, leisure activities, and industrial sites. From the 28 sentences, seven were randomly selected to be used as test sentences during the retrieval phase. For those test sentences, we generated a true and a false version for each of the four attributes (e.g., True: “In Velbert you can find a bicycle museum”, False: “In Velbert you can find an aircraft museum”). This resulted in 56 test statements (7 sentences * 4 attributes * 2 correctness). To control for effects of city names, each sentence had two possible names (e.g., Velbert was replaced by Zehdenick for half of the participants). Eight additional sentences and their respective test statements were generated for the training block.

2.3.4 Procedure

The experiment starts with two practice trials, followed by a free gaze block (8 experimental trials), and a gaze manipulation block (20 experimental trials). Each trial consisted of an encoding phase, which was identical in all conditions, and a retrieval phase, which differed between conditions (see Figure 2.1).

Encoding phase. In the encoding phase of each trial, four sentences were auditorily presented. For each sentence, a loudspeaker was shown in one of the four spatial areas. Importantly, the speaker symbol provided the only link between the sentence and the spatial area, and it was completely irrelevant for successful completion of the task.

Retrieval phase. In the retrieval phase, participants were auditorily presented with a test statement for one of the four encoded sentences and had to press one of two keys on the keyboard to indicate whether the statement was true or false (forced choice). Pressing the key was possible from the beginning of the retrieval phase. There was no time limit for the response, but participants were instructed to respond as quickly and accurately as possible.
The retrieval phase differed between gaze conditions as shown in the lower part of Figure 1. In order to assess spontaneous looking-at-nothing as a function of response accuracy, the experiment started with the free gaze block consisting of 8 trials in which participants gazed freely during the retrieval phase. Subsequently, participants completed the gaze manipulation block that consisted of 20 trials in which we assessed the effects of gaze behaviour on response accuracy. In 12 trials of this block, gaze behaviour during retrieval was manipulated by the spatial cue. In the congruent condition, the cue appeared in the area associated with

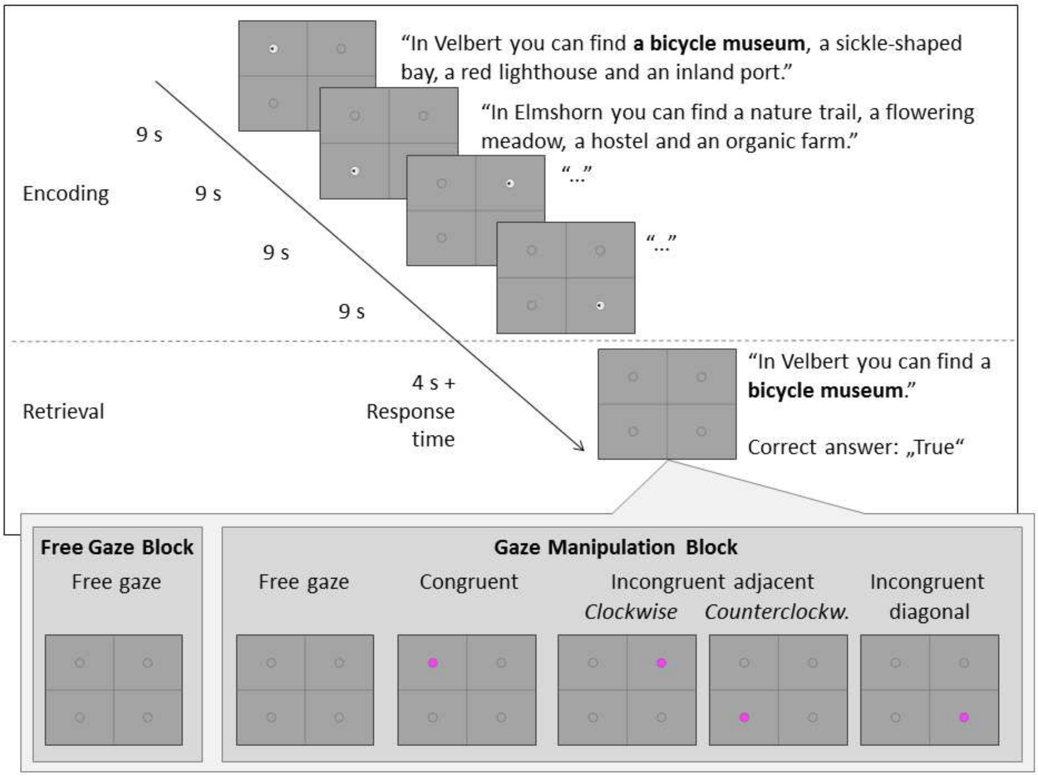

Figure 2.1 Example trial with to-be encoded sentences and a true statement probing the test sentence in the retrieval phase. In this example, the relevant area is the top left area, as this is the location associated with the test sentence. At the bottom of the figure, eye movement conditions in the retrieval phase of the different experimental blocks are illustrated (see main text for a more detailed description).

the tested sentence (4 trials). In the incongruent condition, the cue appeared either in the diagonal area (4 trials) or in one of the adjacent areas (clockwise or counterclockwise, 4 trials). Each participant saw the spatial cue only in one of the adjacent areas. Half of the participants saw it in the clockwise area, and the other half saw it in the counterclockwise area. Therefore, for each participant, the different cued locations (congruent, adjacent and diagonal) were tested equally often. In the remaining 8 trials of the gaze manipulation block, no spatial cue was presented. Trials with and without spatial cues were intermingled during the block. We selected this design, because it enabled us to maximize the salience of the spatial cue itself (because the gaze cue appeared only in 12 out of 20 trials) and ensured that the different cued locations were equally salient (because they were tested with equal frequency). Equal salience of the locations is important, because otherwise differences in gaze behaviour might be caused by differences in salience, rather than by effects of memory retrieval.

The order of assignment of sentences to blocks and conditions was counterbalanced in four ways – the order of presentation and the position of the speaker symbol during encoding, as well as the order of statement presentation and gaze manipulation conditions during retrieval.

2.4 Results

Mean fixation proportion, based on number of fixations (cf. Richardson & Spivey, 2000), was aggregated per trial and participant. Practice trials were not analyzed. A total of ten experimental trials were excluded (1.3 % of all trials), because participants pressed the answer button before listening to the statement (Response time < 1 s).

2.4.1 Spontaneous Looking-at-Nothing During Memory Retrieval in the Free Gaze Block

LAN across all trials. To assess spontaneous looking-at-nothing during memory retrieval, we analyzed fixation proportions in the 8 trials of the free gaze block. The spatial area that corresponded with the to-be retrieved sentence was coded as a relevant area and the other three areas as irrelevant areas 1-3 in a clockwise direction. Table 2.1 shows mean fixation proportions and results of contrast tests (Rosenthal, Rosnow, & Rubin, 2000). A contrast weight of three indicates the relevant spatial area in which participants were expected to fixate most if they exhibited LAN. The three irrelevant spatial areas were given a contrast weight of -1. Overall, participants exhibited looking-at-nothing behaviour, as indicated by the higher proportion of fixations in the relevant area, than in any of the irrelevant areas.

LAN for correct and incorrect responses. To test the relationship between spontaneous eye movements and response accuracy, we analyzed fixation proportions in trials with correct responses (74.1 % of trials in the free gaze block) and trials with incorrect responses (25.9 % of trials in the free gaze block). Looking-at-nothing behaviour was indeed stronger when participants answered correctly, than when they answered incorrectly. Strong looking-at-nothing behaviour is defined as fixating most often on the relevant area during a correct trial. During incorrect trials, the proportion of fixations in the relevant area decreased and participants showed an increased tendency to gaze in the diagonal area (Table 2.1). To compare eye movement patterns between correct and incorrect trials, we analyzed the fixation proportions in the four spatial areas for those 24 participants who gave both correct and incorrect responses. A repeated-measures ANOVA testing fixation proportions confirmed a significant interaction between the Spatial Area (relevant, irrelevant 1, irrelevant 2, irrelevant 3) and Response Accuracy (correct, incorrect) factors, $F(3,69) = 6.32$, $p = .001$, $\eta_p^2 = .22$, indicating that fixation patterns indeed differed between correct and incorrect trials.

Table 2.1 Mean fixation proportions (*SD s*); effect sizes (Hedges' *g*), *t* statistics, and *p* values for the contrasts of spatial area for all cases, only correct and only incorrect responses during the *free gaze block*.

	Spatial area				Contrast			
	Relevant	Irrelevant 1	Irrelevant 2	Irrelevant 3	*n*	*t*	*p*	*g*
Contrast weight	**3**	-1	-1	-1				
Fixation proportions								
All cases	**0.36 (0.12)**	0.23 (0.08)	0.21 (0.09)	0.20 (0.07)	28	13.0	<.001	2.5
Correct responses	**0.38 (0.13)**	0.26 (0.10)	0.18 (0.09)	0.18 (0.09)	28	12.2	<.001	2.3
Incorrect responses	**0.30 (0.23)**	0.14 (0.11)	0.36 (0.23)	0.21 (0.16)	24	4.9	<.001	1.0

Note: Bold values indicate the spatial area with a contrast weight of 3, i.e., in which participants were expected to fixate most in each condition.

2.4.2 Eye Movements and Response Accuracy in the Gaze Manipulation Block

Manipulation check. Before analyzing response accuracy and response times as an effect of gaze manipulation, we tested whether the gaze manipulation was successful. Therefore, we analyzed fixation proportions in each of the gaze conditions (congruent, incongruent clockwise, counterclockwise, and diagonal). In each of those conditions, the manipulation of gaze behaviour would be successful if participants showed more fixations in the area with the spatial cue than in any other area. To test this, contrast weights were set to +3 for the area where the cue was presented and to -1 for the other three areas. The upper part of Table 2.2 shows mean fixation proportions and results of contrast tests for each location of the spatial cue in each of the gaze conditions. In each condition, participants fixated significantly more often in the area where the spatial cue was presented than in any other area, confirming that the gaze manipulation was successful. The lower part of Table 2.2 shows that in the absence of the spatial cue (i.e., during the free gaze trials of the manipulation block), participants showed looking-at-nothing as expected.

Response accuracy. To test effects of the gaze manipulation on response accuracy, we compared response accuracy between congruent, incongruent adjacent and incongruent diagonal trials. As predicted, response accuracy was higher in the congruent than in both incongruent conditions (Figure 2.2, left panel). This result was confirmed by a contrast test assigning a weight of +2 to the congruent and -1 to the adjacent and diagonal conditions, $t(27) = 2.209$, $p = .04$, $g = .42$. Response accuracy in the free gaze trials of the gaze manipulation block was 81.5 % (*SD* = 16.4 %), which was right in between the congruent and incongruent conditions and did not differ significantly from either one (congruent: $t(27) = 1.20$, $p = .24$; $g = .23$; incongruent adjacent: $t(27) = 0.76$, $p = .45$, $g = .14$; incongruent diagonal: $t(27) = 0.88$, $p = .39$, $g = .17$).

Table 2.2 Mean fixation proportions (*SDs*); effect sizes (Hedges' *g*), *t* statistics, and *p* values for the contrasts of spatial area for the congruent, incongruent and free gaze conditions during the *gaze manipulation block*. A contrast weight of three marks the spatial area in which participants were expected to fixate most in each condition.

	Spatial area				Contrast			
	Relevant	Irrelevant 1	Irrelevant 2	Irrelevant 3	*n*	*t*	*p*	*g*
Congruent								
Contrast weight	**3**	-1	-1	-1				
Fixation proportions	**0.47 (0.23)**	0.16 (0.09)	0.19 (0.09)	0.17 (0.10)	28	9.10	<.001	1.7
Incongruent clockwise								
Contrast weight	-1	**3**	-1	-1				
Fixation proportions	0.28 (0.19)	**0.37 (0.27)**	0.16 (0.09)	0.19 (0.15)	14	12.61	<.001	3.4
Incongruent counterclockwise								
Contrast weight	-1	-1	-1	**3**				
Fixation proportions	0.20 (0.15)	0.18 (0.12)	0.15 (0.10)	**0.48 (0.27)**	14	5.12	<.001	1.7
Incongruent diagonal								
Contrast weight	-1	-1	**3**	-1				
Fixation proportions	0.21 (0.16)	0.15 (0.10)	**0.48 (0.25)**	0.17 (0.11)	28	15.25	<.001	2.9
Free gaze								
Contrast weight	**3**	-1	-1	-1				
Fixation proportions	**0.29 (0.12)**	0.22 (0.07)	0.25 (0.10)	0.24 (0.08)	28	9.11	<.001	1.7

Note: Bold values indicate the spatial area with a contrast weight of 3, i.e., in which participants were expected to fixate most in each condition.

Response times. As a second measure indicating the availability of information held in memory, we compared response times between the congruent and the two incongruent conditions (Figure 2.2, right panel). As expected, averaged median response times were shorter in the congruent condition, than in the incongruent adjacent and incongruent diagonal conditions. This result was confirmed by a contrast test assigning a weight of -2 to the congruent and +1 to the adjacent and diagonal conditions, $t(27) = 2.210$, $p = .04$, $g = .42$. Median response times in the free gaze trials of the gaze manipulation block was 1688 ms ($SD = 283$ ms), which was right in between the congruent and incongruent conditions and did not differ significantly from either one (congruent: $t(27) = 0.61$, $p = .55$; $g = .12$; incongruent adjacent: $t(27) = 1.11$, $p = .28$, $g = .21$; incongruent diagonal: $t(27) = 1.33$, $p = .19$, $g = .25$).

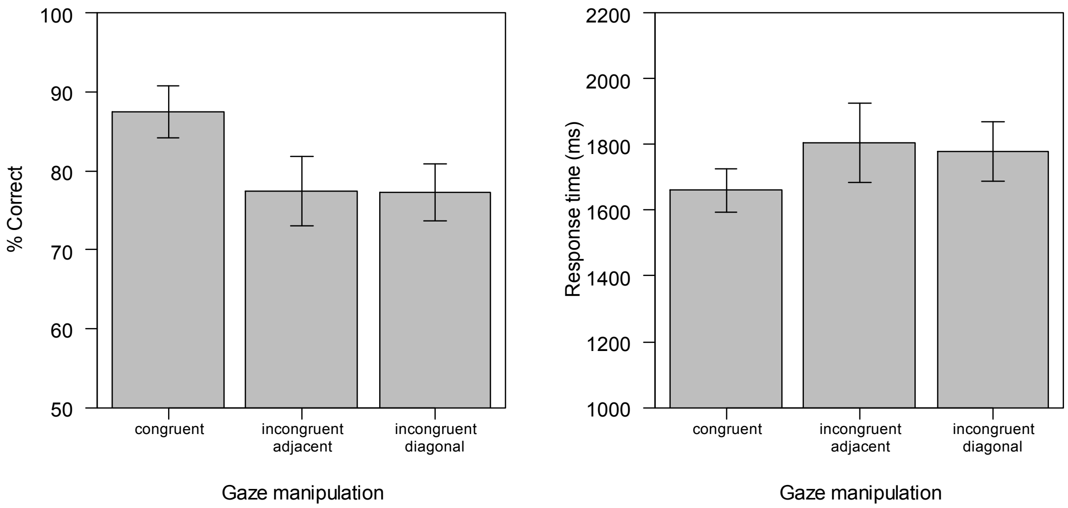

Figure 2.2 Mean percent correct responses (left) and average median response times (right) for the congruent, incongruent adjacent and incongruent diagonal conditions. Error bars represent one standard error.

2.5 Discussion

Recent studies have found a functional relationship between eye movements and the retrieval of visuospatial information from memory (Johansson et al., 2012; Johansson & Johansson, 2014; Laeng et al., 2014; Laeng & Teodorescu, 2002). However, it is unclear whether such a relationship extends to the retrieval of verbal information (Richardson et al., 2009). Our results help to answer this question by clarifying the relationship between gaze behaviour and the retrieval of verbal information in two different ways: We tested (1) gaze behaviour as a function of retrieval performance by comparing looking-at-nothing during correct and incorrect responses and (2) retrieval performance as a function of gaze behaviour by comparing response accuracy and response times during congruent and incongruent fixation conditions.

An analysis of looking-at-nothing as a function of response accuracy in the memory retrieval task revealed stronger looking-at-nothing when participants correctly retrieved information than when they responded incorrectly. This finding is comparable to results from Martarelli and Mast (2010), who demonstrated a similar effect for preschool children on visuospatial material. The decrease of looking-at-nothing during incorrect responses could be an indication of the utility of looking-at-nothing in the memory retrieval process. However, this effect should be interpreted with caution, because the direction of the assumed causal relationship is not clear. When responding incorrectly, a failure to retrieve the correct information from memory might have reduced the likelihood of activating the related spatial index, thereby causing reduced LAN. At the same time, a failure to activate the relevant spatial index might have reduced the likelihood of retrieving the correct information, thereby causing an incorrect response.

The only method that allows for drawing a causal conclusion about the effect of eye movements on memory retrieval is the explicit manipulation of eye movements as independent variable (cf. Richardson et al., 2009), as implemented in the second block of our experiment. Our results from this block provide evidence for a functional relationship between looking-at-nothing and retrieval of verbal information from memory. Response accuracy in the retrieval phase was higher and response times were shorter if participants' gazes in the retrieval phase had been manipulated towards the relevant spatial location (congruent condition); compared to when gaze has been manipulated away from the relevant location (incongruent adjacent and diagonal conditions). To our knowledge, this is the first evidence that clearly shows a functional relationship between eye movements and the retrieval of verbal information from memory.

The functional relationship between eye movements and memory retrieval for visuospatial information has previously been explained as an overlap between processes engaged in encoding and retrieval of a past event stored in episodic memory (Johansson et al., 2012; Johansson & Johansson, 2014; Laeng et al., 2014; Laeng & Teodorescu, 2002). Our results extend this literature by showing that eye movements also play a functional role in the retrieval of verbal information from memory. This holds even if the spatial information is not relevant to the task and there is no demand to learn the spatial information (e.g., Richardson & Spivey, 2000).

Furthermore, our results are consistent with a grounded perspective on cognition, which assumes that behavioural re-enactment (including body posture, hand- and eye movements) of the encoding stage aids retrieval (Barsalou et al., 2003; Barsalou, 2008; Kent & Lamberts, 2008; Spivey, 2007; Wilson, 2002). Cognitive processes, like memory retrieval of verbal information, are not independent of oculomotor processing. Instead, they interact with each other and form continuous perception-action cycles out of which cognition emerges (Anderson & Spivey, 2009; Neisser, 1976; Spivey & Dale, 2011). Thus, oculomotor processes like gazing towards a presently empty, but previously associated spatial location can impact retrieval performance.

Re-enactment of processes that occur during encoding can account for superior memory performance in the congruent condition. In the incongruent conditions, memory retrieval might have been disrupted, because the salient spatial cue that we introduced to manipulate gaze behaviour prevented participants from gazing at the relevant spatial location (Laeng et al., 2014; Postle, Idzikowski, Sala, Logie, & Baddeley, 2006). Thus, the gaze manipulation interfered with the participants' tendency to look at the associated spatial location, thereby degrading memory retrieval performance. The fact that retrieval performance in the free gaze condition of our experiment was observed to fall in between the congruent and incongruent conditions suggests that facilitation (in the congruent condition) as well as impairment (in the incongruent condition) might play a role. It should be noted that conclusions drawn from a comparison between gaze behaviour under free gaze conditions and gaze manipulation conditions are difficult, because gaze manipulation might impose an additional cognitive load, thereby reducing retrieval performance relative to free gaze (Johansson et al., 2012; Martarelli & Mast, 2013; Mast & Kosslyn, 2002). Still, future research should investigate the degree to which processes of facilitation and impairment affect retrieval performance in the looking-at-nothing paradigm, thereby advancing our understanding of the nature of the functional relationship between eye movements and memory retrieval.

In the current study, gaze was manipulated by using a salient spatial cue, which attracted participants' attention either towards (congruent) or away (incongruent) from the relevant location. Our results show that the effects of gaze manipulation on retrieval performance persist even with a primarily attention-driven manipulation. This finding is consistent with Richardson and Spivey (2000) who found that it is not the oculomotor movement of the eyes per se that guides the eyes back to associated spatial locations, but instead gaze is driven by shifts in visuospatial attention (see also Godijn & Theeuwes, 2012). It is also in line with research by Grant and Spivey (2003) and Thomas and Llears (2009), who showed that shifting ones' attention, in comparison to moving ones' eyes in a way that corresponds to the solution of an insight problem, was sufficient to raise success rates. A possible interpretation of the above results could be that it is the shift in attention, rather than the eye movements per se, that causes the functional relationship between looking-at-nothing and memory retrieval (cf. Huettig et al., 2011; Theeuwes et al., 2009). A more detailed investigation of this assumption will improve our understanding of the utility of gaze behaviour and should be a topic for future research.

In conclusion, our results show that even if verbal information, that is only loosely associated with a spatial location, is retrieved from memory, the process of remembering is accompanied by eye movements to associated spatial locations. In addition, we found that retrieval performance varies as a function of gaze behaviour. Therefore, our results provide additional support for the idea that re-enactment of processes that occur during encoding increases the likelihood of successful episodic memory retrieval (cf. Tulving, 1983) and show that this phenomenon holds regardless of the nature of the to-be-retrieved information.

3 Looking-at-nothing and Practice

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3.1 Abstract

People fixate on blank locations if relevant visual stimuli previously occupied that location; the so-called "looking-at-nothing" effect. While several theories have been proposed to explain potential reasons for the phenomenon, no theory has attempted to predict the stability of this effect with practice. We conducted an experiment in which participants listened to four different sentences. Each sentence was associated with one of four areas on the screen and was presented 12 times. After every presentation participants heard a statement probing one sentence, while the computer screen was blank. More fixations were found to be located in areas associated with the probed sentence than in other locations. Moreover, the more trials participants had completed, the less frequently they exhibited looking-at-nothing behaviour. Fixations on blank locations seem to occur when an attempt is made to retrieve information associated with a spatial location as long as it is not strongly represented in memory.

Keywords: Eye tracking, practice, spatial cognition, mental representation, working memory

3.2 Introduction

When processing information from the visual world, human cognition integrates visual and auditory input with abstract, higher level mental representations (e.g., Huettig et al., 2011). Reactivation of such a memory representation leads the gaze back to spatial locations or areas that were previously occupied by relevant information. For example, when we mention something about a table presented on a whiteboard, we might point towards the whiteboard, even if the table is no longer there anymore.

Richardson and Spivey (2000) were among the first to show a close link between eye movements, auditory information processing and semantic information processing, in an information-retrieval task. Participants were presented with a spinning cross in one of four equal-sized areas on a computer screen together with spoken factual information. After four facts were presented, participants heard a statement probing one of the presented facts and had to judge the truth of the statement. During this retrieval phase the computer screen was blank. Participants fixated more in the relevant area where the sought-after information was presented compared to other areas on the screen.

This so-called “looking-at-nothing” behaviour (e.g., Hoover & Richardson, 2008; Richardson & Kirkham, 2004) also occurs when the probed information is presented visually (Laeng & Teodorescu, 2002; Renkewitz & Jahn, 2010; Spivey & Geng, 2001), when information is anticipated (Altmann & Kamide, 2007), in light and in complete darkness (Johansson et al., 2006), and for simple (Brand & Stark, 1997) and more complex pictures (Johansson et al., 2006; Johansson, Holsanova, & Kenneth, 2010).

Ferreira et al. (2008) assume a memory representation of an object or event that integrates visual, auditory and spatial information and leads to a corresponding visual, linguistic, spatial, and conceptual representation. When one part of this integrated memory representation is reactivated, other parts are retrieved, as well. This in turn causes gazing behaviour toward the location where the information was previously presented. For example, seeing a table on a whiteboard leads to the activation of a visual as well as conceptual representation of the table. Additionally, spoken language leads to the formation of a linguistic representation. The visual world leads to the activation of a spatial index (Pylyshyn, 2001), which can be used later to direct our gaze back to the area on a whiteboard, where the figure was previously presented.

Huettig et al. (2011) recently proposed a general framework to describe how linguistic and visual representations are bound together in an integrated memory representation. Their model, like that of Ferreira et al. (2008), assumes the integration of information in a connected visual, linguistic, spatial, and conceptual representation. It further includes ideas proposed by Altmann and Kamide (2007), Knoeferle and Krocker (2007), and Spivey (2007). Here, we briefly introduce their framework. It is worthwhile to note that they include a detailed description of how integrated memory representations can be linked to existing theories of long-term and working memory (cf. Baddeley, 2000). Huettig et al. (2011) propose that language-vision interactions are based on long-term memory, where conceptual representations (e.g., the concept of a figure or of a whiteboard) are derived from. Therefore, long-term memory serves as a stable knowledge base. It is then working memory that grounds cognition in space and time and leads to the formation of short-term connections between objects (e.g., spoken language, a figure, and a whiteboard). Contents of working memory are linked to contents of long-term memory via spatial indices. Because of this association working memory can instantiate a gaze back to the object. In describing connections between memory representations, Huettig et al. (2011) assume that the stronger the association between the linguistic and conceptual representations the higher "the probability of triggering a saccadic eye-movement" (p. 5).

Richardson et al. (2009) share Huettig at al.'s (2011) general idea of an integrated memory representation. In contrast, however, they suggest that only sparse internal representations are built during the encoding of information. They assume that during information retrieval, an eye movement can be launched to the associated area in order to gather more information. This occurs when the spatial pointer (i.e., the visual part of the integrated memory representation) does not include the searched information: "If the pointer's tag does not include the attribute, then the pointer's address to the external environment is the next obvious resource" (Spivey, 2007, p. 298). The link between information sampling from the environment and eye movements can be understood as the covert orienting of visual-spatial attention (e.g., Hoffman & Subramaniam, 1995). Targeting a position makes it necessary to allocate attention towards that place. Because it is impossible to make an eye movement without an attentional movement (Shepherd, Findlay, & Hockey, 1986), attending to information stored in an integrated memory representation leads to eye movements towards associated spatial areas.

Summarizing, we conclude that during the encoding of information a memory representation is formed from different modalities. However, theories diverge in terms of how much information is included in the memory representation and how this in turn affects the looking-at-nothing behaviour. Ferreira et al. (2008) assume that the probability of triggering an eye movement increases with the strength of the association between the linguistic and conceptual representation. Consequently, one could predict that looking-at-nothing behaviour becomes stronger with an increasing association between these representations. Spivey (2007), on the other hand, proposes that looking-at-nothing mainly occurs for the purposes of gathering information not yet included in the mental representation. In line with this one might conclude that looking-at-nothing diminishes as relevant information is included in the memory representation.

To test these assumptions we varied the degree to which information is included in memory representation. More precisely, we manipulated the degree of practice in a task, where auditory information, which is associated with contents from a visual scene, has to be retrieved from memory. With more practice, the strength with which retrieval-relevant information is represented in memory increases (e.g., Anderson & Schooler, 1991). If looking-at-nothing increases with practice, then Huettig et al.'s assumptions would be supported. On the other hand, if looking-at-nothing decreases with practice, our findings would support Spivey (2007) and conclude that looking-at-nothing varies with the degree of relevant information included in the mental representation.

3.3 Experiment

To test looking-at-nothing behaviour under different levels of practice we conducted an experiment in which participants were presented with four different sentences. Each sentence described an artificial scene. The same set of four sentences was presented in each of 12 experimental trials. After every presentation trial a retrieval phase followed in which one of the four sentences was probed. In every trial each sentence was associated with the same spatial location on a computer screen.

3.3.1 Method

Participants. Eighteen students (14 female; age *M* = 22.8) from Technische Universität Chemnitz participated in the experiment. All reported normal or corrected-to-normal vision with contact lenses. All participants were native German speakers.

Apparatus and material. Participants were seated in front of a computer screen at a distance of 630 mm and instructed to position their head in a chin rest. The eye tracker system SMI iView REDpt was used to sample data of the right eye at 50 Hz with a precision of 0.05°. Data were recorded with iView X 1.7 and analyzed with BeGaze 2.3 and MatLab 7.0.1 software programs. Stimuli in the experiment were presented using E-Prime 2.0 on a 380 mm × 305 mm computer screen with a resolution of 800 × 600 pixels.

The visual stimuli consisted of a grid dividing the screen into four equal-sized areas with a fixation cross at the center of the grid. Each set of four sentences was associated with the same symbol – a black circle with a white loudspeaker in it – which appeared in one of the four areas of the grid depending on the sentence that was presented.

The auditory stimuli presented in the presentation trial consisted of four prerecorded sentences each describing three attributes of an artificial scene (e.g., "There is a place with a purple lighthouse, a sickle-shaped bay, and a wooden church."). To test gaze behaviour in the retrieval phase, we generated 24 statements: A true and a false version for each of the four statements multiplied by three attributes (The false statement probing the example sentence from above was "There is a place with a wooden cottage."). Figure 3.1 shows 1 of the 12 experimental trials.

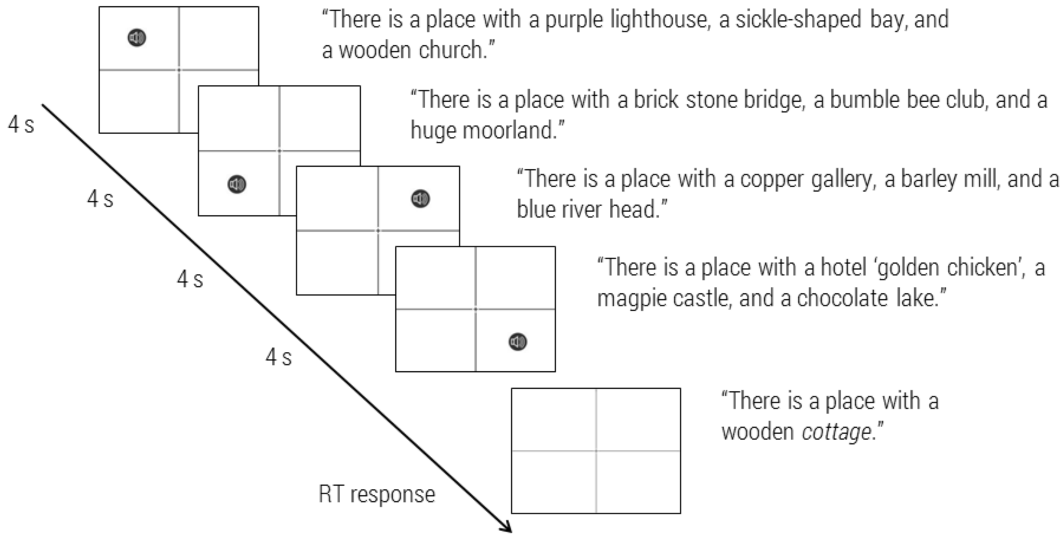

Figure 3.1 Example trial with the four experimental sentences (presentation phase) and a statement probing the first sentence (retrieval phase). Original materials were in German.

Procedure. To mask study intentions, students were told they were participating in a study concerning pupil dilation that involved solving a memory task. No instructions concerning gaze behaviour were provided. The eye tracker was calibrated using a 9-point calibration method. This procedure lasted between 5 and 10 min. Subsequently, the 12 experimental trials started. In each of the 12 trials, the same four sentences were presented in random order. Every sentence always appeared with the symbol in the same area on the screen at presentation duration of 30 s.

After presentation of the fourth sentence within a trial, the retrieval phase followed. Participants heard a statement, which referred to a fact from one of the four sentences, and judged it to be true or false. To observe participants' gaze behaviour, they were intentionally not instructed to reply as soon as possible. Presentation of one statement lasted 4 s. Statements were randomly assigned to trials and participants with the restriction that every statement was probed once for each participant. Participants had to answer the true or the false version of a statement balanced across trials and participants such that every participant was presented with six true and six false statements. A true statement was recorded when participants responded verbally with "right" and a false statement with "wrong". Immediately following this response, the investigator pressed a key signaling the start of the next trial. In this way, participants were not required to look at the keyboard (This procedure was chosen to prevent gazing away from the monitor towards the keyboard, which could have led to loss in quality of eye tracking data). After depressing the key, the investigator noted the participant's response on a sheet of paper. During the 12 experimental trials and their retrieval phases, gaze data were recorded. Afterwards, participants filled out a questionnaire which interrogated demographic variables and the assumed goal of the study. Before leaving, participants were informed about the true nature of the study.

Analysis. To assess participants' performance, we collected data on the accuracy of their responses and response times (i.e., the time beginning with the retrieval phase and ending with a participant's reply as noted by the investigator). As reaction times are prone to error through outliers (e.g., when an investigator does not stop recording immediately upon a participant's response) we did not exclude outliers but used median reaction times for further analysis.

To assess looking-at-nothing, gaze data from the beginning of the retrieval phase to a participant's reply (i.e., analogous to response time) was analyzed. Four adjacent "areas of interest" (AOIs) were defined corresponding to the four areas on the screen. Numbers of fixations in every AOI were counted per person and per trial. A fixation was defined as having a minimum duration of 100 ms and a maximum dispersion of 100 pixels (1.3° visual angle). The AOI associated with a probed sentence is called the "relevant area". Gaze behaviour was analyzed, whereby trials were discarded in which tracking data was missing for > 40 % of the trial duration (8 % of all trials). Missing tracking data was caused by blinks, lost pupil or corneal reflectance, or looking away from the screen.

To test the independent variable practice, we aggregated the number of fixations in the AOIs as well as the performance data over sets of four experimental trials. This allowed us to compare three conditions of practice: block 1 (consisting of trials 1–4), block 2 (trials 5–8), and block 3 (trials 9–12).

Number of fixations and median reaction times were only analyzed for trials that were answered correctly.

3.3.2 Results

Performance measures. Overall, mean percentage of correct responses to the statements was M = 87.8 % (SD = 20.8 %), suggesting that the material was neither too difficult to memorize nor too easy to learn. A one-way repeated measures ANOVA revealed a significant effect for accuracy over the three blocks, $F(2,34) = 11.04$, $p < .001$, $\eta_p^2 = .40$. Bonferroni post-hoc tests showed an increase in performance from the first to the second block, M_{b1} = 73 % vs. M_{b2} = 93 %, $p = .004$, and from the first to the third block, M_{b1} = 73 % vs. M_{b3}=97 %, p =.005. There was no significant change in performance from the second to the third block, M_{b2} = 93 % vs. M_{b3} = 97 %, $p = 1.00$.

The median reaction time to the statement in the retrieval phase was 6206 ms (SD = 1617 ms). Over the three blocks of practice participants became faster in correctly responding, Greenhouse-Geisser-corrected $F(1,48;34) = 9.61$, $p = .002$, $\eta_p^2 = .36$.

Bonferroni post-hoc tests confirm a decrease in the median reaction times from the first to the second block M_{b1} = 7211 ms vs. M_{b2} = 5798 ms, p = .016 and from the first to the third block, M_{b1} = 7211 ms vs. M_{b3}=5608 ms, p = .009. Again, there is no difference between the second and the third block, M_{b2} = 5798 ms vs. M_{b3} = 5608 ms, p = 1.00. Response accuracy and median reaction times showed that the practice manipulation was successful. With more practice, participants answered correctly more often and replied more quickly to the statements.

Mean number of fixations.

Exemplary gaze behaviour of a typical participant. Figure 3.2 shows scan paths of a typical participant for the presentation and the retrieval phase of three trials, where the relevant area was on the bottom right. Lines show saccades and circles represent fixations with bigger

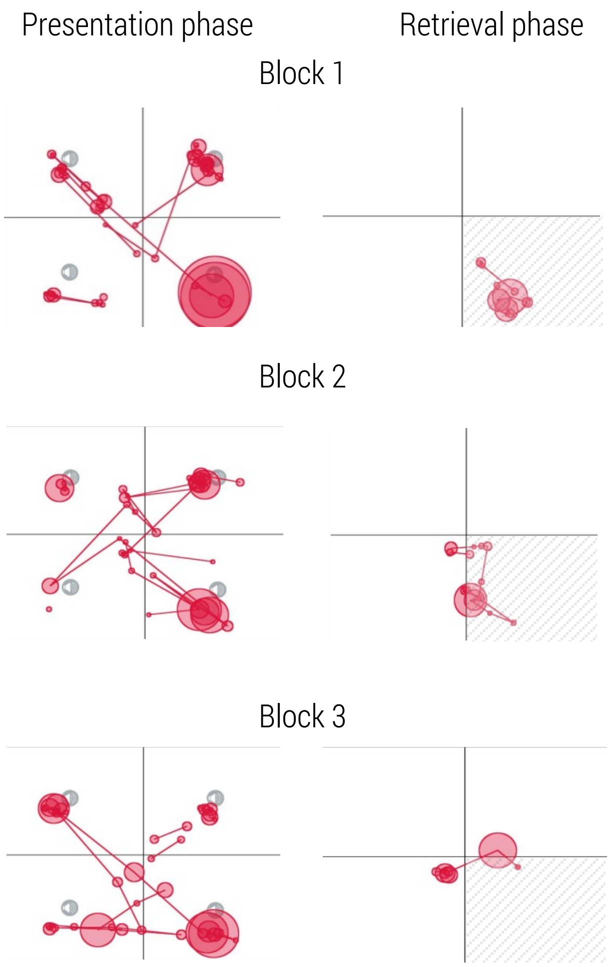

Figure 3.2 Scan paths of one participant for a trial in block 1 (top), a trial in block 2 (middle) and a trial in block 3 (bottom) with the critical area at the bottom right. Left: presentation phase (scan paths of four sentence presentations)[2], right: retrieval phase.

[2] Longer fixations at the bottom right area are only shown by displayed data and not systematically. To control for gaze biases the critical area was randomized across trials.

circles indicating longer fixations. Scan paths on the top left and right side of Figure 3.2 show a trial from block 1. In this trial, the sentence that was associated with the symbol in the bottom right area of the screen was probed for the first time. Scan paths on the left and right side in the middle of Figure 3.2 show a trial from block 2. In this trial, the sentence on the bottom right was probed for the second time. Scan paths on the left and right side on the bottom of Figure 3.2 show gaze behaviour when the sentence was probed for the third time (block 3). Comparing scan paths from top to bottom on the left side of Figure 3.2, scan paths reveal that throughout the experiment the participant kept on following the symbols during the presentation phase. In comparison, gaze behaviour in the retrieval phase (Figure 3.2, right) seems to change over the experiment. In block 1, the participant directs several gazes to the relevant area (Figure 3.2, top right). With increasing practice, fewer fixations in the relevant area are made (middle and bottom right).

Aggregated gaze behaviour. Figure 3.3 shows the proportion of fixations in the relevant area during the retrieval phase. Proportions were aggregated for each block and across participants. Participants showing looking-at-nothing behaviour should fixate in the relevant area during the retrieval phase. To test this, for each block, we compared the proportion of fixations in the relevant area with a chance level of 25 %. In block 1, the proportion of fixations in the relevant area (37.2 %) is indeed above chance, $t_{b1}(17) = 2.09$, $p = .05$, $g = .99$. In blocks 2 and 3 the proportion of fixations in the relevant area were at chance levels, mean proportion block 2: 17.9 %, $t_{b2}(17) = -1.73$, $p = .10$, $g = .82$; mean proportion block 3: 28.5 %, $t_{b3}(17) = 0.81$, $p = .43$, $g = .38$. These results suggest that looking-at-nothing diminished from block 1 to block 2 and that the proportion of fixations did not vary meaningfully from chance in block 3.

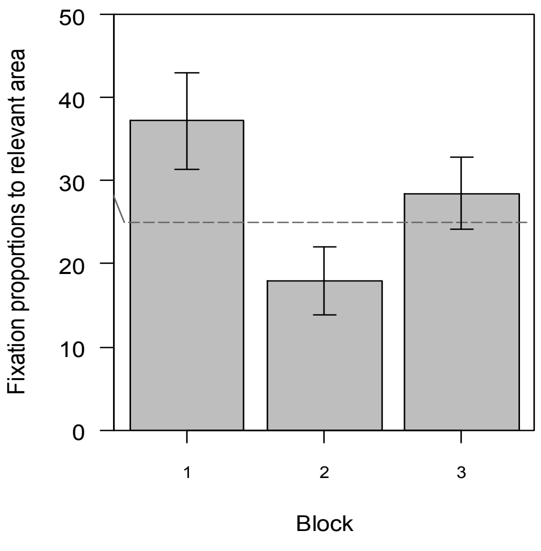

Figure 3.3 Fixation proportions in the relevant area across blocks. Error bars represent one standard error, dotted line indicates chance level. Error bars show standard errors.

3.4 Discussion

Theories on the link between eye movements and auditory and semantic information processing (Huettig et al., 2011) assume that during the encoding of information an integrated memory representation is formed from different modalities. However, these theories do not agree on how much information is included in the memory representation. Using the looking-at-nothing paradigm, we tried to shed some light on this question.

Assuming an integrated memory representation as proposed by Ferreira et al. (2008), the probability of triggering an eye movement during retrieval of information from memory will increase with the strength of the association between the different parts of the representation. Spivey (2007), on the other hand, proposed that only sparse internal representations are built during the encoding of information. Consequently, eye movements during memory retrieval occur mainly to gather information that is not yet included in the mental representation. According to Ferreira et al. (2008), looking-at-nothing should increase with practice, while for Spivey (2007) the same behaviour should diminish with practice.

Practice was induced by presenting participants with a set of four sentences, 12 times. Each presentation phase was followed by a retrieval phase where one sentence was probed. To test whether the manipulation was successful, we first checked if participants showed increasing performance in the retrieval task. Results show that over the three blocks, participants indeed replied with increasing accuracy and speed to the facts probing the presented sentences. Accuracy as well as response times revealed that the performance increase was stronger from the first to the second block, than from the second to the third block. It seems that over the three blocks of practice memory associations for the sentences were strengthened leading to more correct and faster responses. Therefore, we conclude that the practice manipulation was successful.

The question we wished to answer was how looking-at-nothing behaviour would be affected by the content of the memory representation. In block 1, participants looked more often to the relevant area on the screen than a chance level of 25 % would predict. In blocks 2 and 3 looking-at-nothing diminished. In both blocks, fixations in the relevant area did not amount to more than that predicted by a chance level of 25 %.

Results of the first block replicated results of Richardson and Spivey (2000), which showed a close relationship between gaze behaviour and language processing. In block 1, information was not strongly represented in memory. Eye movements were launched to the relevant area on the screen in order to collect information from the visual scene. For blocks 2 and 3 we assumed that the looking-at-nothing behaviour would become stronger or diminish, respectively. Our results were not in line with the predictions of Huettig et al. (2011), which stated that looking-at-nothing becomes stronger as the association in memory is strengthened. While performance improved over the three blocks, looking-at-nothing did not increase in strength. Our results seem to support the assumption of Spivey (2007) that looking-at-nothing behaviour is executed to gather more information from the environment. In blocks 2 and 3, the memory representation might have included all relevant information. Thus, addressing an eye movement to the relevant area on the screen became “unnecessary”.

We found that looking-at-nothing varies with the content of the memory representation. This supports the work of Richardson et al. (2009), who assume the existence of an internal memory story, whereby all relevant information is stored in an integrated memory representation, and an external memory store (O’Regan, 1992), which assumes only sparse memory representations and uses a spatial index to address the visual world. Moreover, these are not mutually exclusive abilities of the cognitive system. Instead, the cognitive system can use both. The question is, when do we rely on an internal memory representation and when on an external memory store? Hoover and Richardson (2008) and Johansson et al. (2010) suggest that looking-at-nothing helps to relieve working memory when information is retrieved from memory. For example, Johansson et al. (2010) presented participants with an auditory description of a complex scene while participants had to fixate the center of a whiteboard. In a second condition they saw the picture of a complex scene but again had to fixate on the center of the picture’s scene. In both conditions, when they had to retell the information they had heard, and when they had to describe the visual scene, they drew the scene with their eyes on the whiteboard and did not maintain a central fixation. In contrast, in a study reported by Brand and Stark (1997), simple block patterns were used. During retrieval of the block pattern, participants were allowed to look freely around the scene but kept a central fixation. Therefore, Johansson et al. (2010) argue that looking-at-nothing behaviour can relieve working memory load when task demands (e.g., a complex scene description) require it.

Applying the findings of Johansson et al. (2010) to our results suggests that when memory load is high, looking-at-nothing is shown. When memory load is low – because all relevant information has been learned – looking-at-nothing behaviour diminishes. Indeed, in block 1 of our study, when the presented material was new to participants, looking-at-nothing was shown. Later, when the material was strongly represented in memory, looking-at-nothing diminished.

Decreased looking-at-nothing behaviour might also be explained as the result of participants realizing over the course of the experiment that the visual area they refixate on no longer includes relevant information and therefore, this behaviour becomes redundant. This implies that participants consciously control their gaze behaviour. However, eye movements as described in the context of the looking-at-nothing effect are a highly automatic and unconscious behaviour (Rayner, 2009). Furthermore, if change in gaze behaviour were due to conscious control (i.e., participants realize that during the retrieval phase, nothing is present anymore), we would then expect looking-at-nothing to diminish within the first block. Looking at data of the first four trials, we could not find such a tendency. Moreover, in the post-questionnaire participants did not report that they controlled their gaze behaviour.

We also realize that looking-at-nothing might not only diminish because participants have learned the material, but because they have given an automatic response to the stimuli that does not include fixations to the relevant area. To rule out this alternative explanation one could present participants with the same sentences throughout the course of the experiment and sentences that change from trial to trial. If it is indeed the content of the integrated memory representation that is responsible for looking-at-nothing behaviour, our results should be replicated in a way that looking-at-nothing behaviour diminishes for stable sentences and does not diminish for new sentences.

From the results of this study it can be concluded that information is represented internally, and that under certain conditions the external world is addressed in order to gather more information (Spivey, 2007). We have further shown that both ways of retrieving information are not necessarily mutually exclusive (Richardson et al., 2009). But, when is knowledge presented internally and when do we use an external memory store? We propose that working memory load may influence the decision to use either an internal or external memory store. However, a distinct boundary need not be imposed between these two modes of storage. Spivey (2007) proposes that knowledge representations can be described in a vague manner. That is, information can belong to both internal and external storages. (Bocklisch, Bocklisch, Baumann, Scholz, & Krems, 2010) highlighted a relationship between the concept of vagueness and knowledge representations. This link could inform future research that tests the usefulness of this approach for the investigation of mental representations.

4 Access of Information from Multimodal Memory Representations

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4.1 Abstract

Recent research suggests that when people retrieve information from memory they tend to fixate on the location where the information had appeared during encoding. We used this phenomenon to investigate if different information is activated in memory when people use a rule- versus a similarity-based decision strategy. In two studies, participants first memorized multiple pieces of information about various job candidates (exemplars). In subsequent test trials they judged the suitability of new candidates that varied in their similarity to the previously learned exemplars. Results show that when using similarity, but not when using a rule, participants fixated longer on the previous location of exemplars that resembled the new candidates than on the location of dissimilar exemplars. This suggests that people using similarity retrieve previously learned exemplars, whereas people using a rule do not. The experiment illustrates that eye movements can provide new insights into the memory processes underlying decision-making.

Keywords: similarity, eye movements, process tracing, looking-at-nothing, multi-cue decision-making, episodic memory

4.2 Introduction

A fundamental distinction in cognitive psychology refers to the contrast between similarity- and rule-based cognitive processes. Although this distinction is intuitively appealing and has stimulated much empirical research, it has proved difficult to pin down on the process level (e.g., Barsalou, 1990; Hahn & Chater, 1998; Milton, Wills, & Hodgson, 2009; Pothos, 2005). One reason could be the core difference between rule-based and similarity-based processes in how information is processed in memory (Hahn & Chater, 1998). This makes the differences between similarity- and rule-based processes difficult to experiment, because memory processes are invisible. For instance, when studying decision processes it is easy to observe what people chose, but not whether people made a choice by focusing on the information provided or by retrieving similar decisions from memory. Recent research has suggested that eye movements can be used to trace information search in memory (Jahn & Braatz, 2014; Renkewitz & Jahn, 2010, 2012; Richardson & Kirkham, 2004; Richardson & Spivey, 2000); we show in the present work that recording eye movements can be used to make differences in memory retrieval between people using similarity- and rule-based strategies visible, providing a possible method for disentangling the two strategies on the process level.

4.2.1 Using Eye Movements to Make Information Search in Memory Visible

Studying cognitive processes that rely on memory, such as categorization, reasoning, problem solving, and decision-making, can be challenging because the processes of interest are not directly observable. Researchers have tackled this problem by developing indirect methods, using self-reports, computational modeling, and reaction times to gain a window into the mind (Anderson, 1987; Bröder, 2000; Johnson & Krems, 2001; Lewandowsky & Farrell, 2011; Mehlhorn et al., 2011; Payne, Bettman, & Johnson, 1993). Although these methods provide valuable data, they also have important drawbacks. For instance, self-reports about memory processes are often inaccurate and incomplete, and asking about them can affect the process itself (Ericsson & Simon, 1980; Renkewitz & Jahn, 2010; Russo, Johnson, & Stephens, 1989).

Alternatively, eye movements can be used to trace information search (Glaholt & Reingold, 2011; Orquin & Mueller Loose, 2013; Peterson & Beck, 2011). Eye movements are quick, frequent, and highly automatic actions (Irwin, 2004; Rayner, 2009; Spivey & Dale, 2011; van Gompel et al., 2007) that have been shown to reflect attention and information search in a variety of tasks, such as concept learning (Nelson & Cottrell, 2007; Rehder & Hoffman, 2005), text comprehension (Allopenna et al., 1998; Altmann & Kamide, 2007; Altmann, 2004; Tanenhaus et al., 1995), and decision-making (Glaholt & Reingold, 2011; Orquin & Mueller Loose, 2013). Lately, evidence has been accumulating that eye movements can also be used to trace memory processes. When people retrieve information from memory they look at spatial locations where the information was originally presented — even if the information is no longer visible (Hoover & Richardson, 2008; Johansson et al., 2012, 2006; Laeng et al., 2014;

Laeng & Teodorescu, 2002; Martarelli & Mast, 2013; Richardson & Kirkham, 2004; Richardson & Spivey, 2000; Spivey & Geng, 2001). In the classic paradigm, Richardson and Spivey (2000) presented participants with a spinning cross in one of four equal-sized areas on a computer screen together with spoken factual information. In a later test phase, participants heard a statement regarding the presented facts and had to judge the truth of the statement. Even though during this retrieval phase the computer screen was blank, participants fixated more often on the spatial area where the sought-after information had been presented than on the other three areas on the screen.

Most likely, people show this “looking-at-nothing” effect because during encoding, information from multiple sources of input, including the locations of perceived objects, is integrated into an episodic memory representation. Once the episodic memory representation is reactivated during retrieval it spreads activation to the motor system, which in turn leads to the execution of eye movements back to the locations linked with the memory representation (Huettig et al., 2012, 2011; Richardson & Kirkham, 2004). The exact role eye movements play in the retrieval process is still debated (e.g., Ferreira et al., 2008; Richardson et al., 2009), but early evidence suggests that eye movements can also facilitate memory retrieval (Johansson & Johansson, 2014; Laeng et al., 2014; Scholz, Mehlhorn, & Krems, 2014).

Recent research suggests that the looking-at-nothing effect can also be used to trace retrieval processes in higher order cognitive processes such as decision-making and diagnostic reasoning. For instance, Renkewitz and Jahn (2010, 2012) found that when participants had to retrieve information about two alternatives to make a decision, they looked at the location where the information about the alternatives had previously appeared. Furthermore, gaze patterns during retrieval were consistent with the information search predicted by the decision strategies participants used. Similarly, Jahn and Braatz (2014) showed that during a diagnostic reasoning task, people tended to look at locations associated with symptoms they had to retrieve from memory to test hypotheses about what caused the symptom. More importantly, the eye movements reflected the diagnostic value of the symptoms and how participants updated their hypotheses about the causes over time. These findings suggest that eye movements are not automatically launched to all associated spatial locations but reflect target-oriented information search in memory during the reasoning process.

In sum, spatial information about the location of information is stored along with the memory of it. Retrieving the respective memory triggers eye movements to the associated locations. These eye movements reflect the currently active memory representation and provide researchers with a new method for monitoring information search in memory. We used this method to differentiate memory processes involved in similarity- and rule-based judgments and decisions.

4.2.2 Memory Retrieval in Similarity- and Rule-based Processes

The distinction between rule- and similarity-based processes is fundamental to understanding human cognition and has stimulated research in a broad range of fields, from categorization and decision-making (e.g., Ashby, Alfonso-Reese, Turken, & Waldron, 1998; Erickson, Kruschke, Blair, Fragassi, Johansen, & Nosofsky, 1998; Persson & Rieskamp, 2009; Pothos & Hahn, 2000) to reasoning (Smith, Langston, & Nisbett, 1992) and language acquisition (Pinker & Prince, 1988). In general, it is assumed that rule-based processes involve the application of previously abstracted knowledge to specific instances (Hahn & Chater, 1998). That is, people form a rule defining the relationship between a specific piece of information and the decision outcome and apply it when confronted with a new decision problem (Bröder et al., 2010; Juslin, Karlsson, & Olsson, 2008; Mata, von Helversen, Karlsson, & Küpper, 2012; Persson & Rieskamp, 2009; von Helversen, Mata, & Olsson, 2010; von Helversen & Rieskamp, 2008, 2009). For instance, when deciding to take one's bike or car in the morning, one could have learned the rule that it is better to take the car when it is raining. In contrast, similarity processes are generally characterized by the retrieval of similar instances or exemplars from memory (Bröder et al., 2010; Hahn & Chater, 1998; Hahn et al., 2010; Juslin & Persson, 2002). That is, when deciding to take the car or the bike in the morning, one might think back to similar occasions and compare how well one fared when taking the bike.

A core theoretical distinction that has been proposed is that the two processes differ in the way mental representations of stored information are accessed (Bailey, 2005; Hahn & Chater, 1998). Similarity-based processes involve comparing the object under consideration to exemplars stored in memory. In contrast, rule-based processes involve processing the information an object under consideration provides according to the processing steps specified by the rule. Accordingly, in a decision task the object's attributes are matched against the conditions for choosing the respective options as specified in the rule. This suggests that similarity-based but not rule-based processes require the retrieval of previously encountered instances from memory. Consistently, similarity-based judgments rely more on episodic memory than rule-based judgments (Hoffmann et al., 2014). However, direct evidence that similarity- and rule-based processes rely on different retrieval processes is scarce (Ashby & O'Brien, 2005). One problem is that differentiating the two processes is far from trivial on a conceptual and empirical level (Barsalou, 1990; Hahn & Chater, 1998; Markman et al., 2005; Pothos, 2005). Research trying to tease apart rule- and similarity-based processes has frequently relied on computational modeling approaches (e.g., Bröder et al., 2010; Juslin et al., 2008; Juslin, Olsson, & Olsson, 2003; Karlsson, Juslin, & Olsson, 2007; Nosofsky & Bergert, 2007; Pachur & Olsson, 2012; Persson & Rieskamp, 2009; Platzer & Bröder, 2013; von Helversen, Karlsson, Mata, & Wilke, 2013; von Helversen et al., 2010). Although computational modeling approaches can provide relevant insights into the cognitive processes underlying behaviour, there are important limitations. First, the decision of which model best describes the data is usually based on some measure of goodness of fit. However, depending on the selected measure the results may diverge considerably (Scheibehenne, Rieskamp, & Wagenmakers, 2013). Furthermore, just because a model can predict the outcome of a decision process does not necessarily mean it also reflects the underlying cognitive processes. Indeed, looking at process data may reveal that a model misses important aspects of the cognitive processes leading to the decision (e.g., Johnson et al., 2008). Accordingly, it seems necessary to complement cognitive modeling approaches with process data to reach a full understanding of the cognitive processes underlying a decision (see also Schulte-Mecklenbeck et al., 2011).

We used the looking-at-nothing effect to clarify how memory processes involved in similarity- and rule-based decisions differ. Specifically, if rule and similarity processes differ in the information that is retrieved from memory when making a decision, it should be possible to make these search processes visible by associating exemplars with specific spatial locations and then tracking the eye movements during the retrieval process to capture information search in memory. If people retrieve exemplars from memory when relying on a similarity-based process, the looking-at-nothing effect would predict that people gaze back at associated exemplar locations. In contrast, if people do not retrieve similar exemplars from memory when using a rule, fixation on the locations associated with exemplars should be rare. Furthermore, when using an exemplar-based strategy the eye movements to exemplar locations should be a function of the exemplars' similarity, because the probability with which an exemplar is retrieved from memory depends on the exemplar's similarity to the object under evaluation (Dougherty, Gettys, & Ogden, 1999; Hintzman, 1988; Nosofsky & Palmeri, 1997).

To test these hypotheses, we conducted two experiments using a multi-cue decision paradigm. We chose this type of problem because the assumption that people rely on rule- and similarity-based strategies to make decisions is widespread (Bröder et al., 2010; Hahn et al., 2010; Juslin et al., 2003, 2008; Karlsson et al., 2007; Pachur & Olsson, 2012; Persson & Rieskamp, 2009; Platzer & Bröder, 2013; von Helversen et al., 2010, 2013).

4.3 Experiment 1

Experiment 1 examined if relying on a rule versus relying on similarity leads to different information retrieval from memory. Participants had to decide if job candidates applying for a position were suitable, that is, whether they should be invited for an interview or rejected. In a training phase participants learned information about two suitable and two unsuitable job candidates. In a subsequent test phase they were instructed to decide if new job candidates should be invited, either by using a rule that was provided to them or by using similarity to the previously learned job candidates (exemplars). To study eye movements, the information about the four exemplars was presented in four different locations on the screen during the training phase. During the test phase we used the eye movements to the exemplar locations to measure memory retrieval.

4.3.1 Method

Participants

We included participants in the experiment only if the tracking validity reached a visual angle smaller than 2°. This was the case for 63 participants. From the 63, we excluded 10 participants from the analyses, 5 because they did not decide according to the instructed strategy and 5 because in the majority of trials less than 60 % of eye movement data was recorded (see Renkewitz & Jahn, 2012, for a similar procedure). The final 53 participants were all students from Technische Universität Chemnitz (34 female; M_{age} = 22.4 years, range 18 – 31 years). All had normal or corrected-to-normal vision with glasses or contact lenses. Participants were randomly assigned to the different strategy conditions, 27 to the rule condition and 26 to the similarity condition. For their participation they received course credit and a performance-dependent bonus (*M* = 4.80 euros). On average, the experiment lasted 60 min.

Apparatus

Participants were seated in front of a 22-inch computer screen (resolution: 1680 × 1050 pixels) at a distance of 630 mm and instructed to position their head in a chin rest. Stimuli were presented using E-Prime 2.0 running on a separate computer. The eye tracker system SMI iView RED120 sampled data of the right eye at 120 Hz and recorded with iView X 2.5 following a 5-point calibration. Auditory material was presented via headphones. All auditory recordings were spoken by a female voice using a shell script in Mac OS X. Participants responded by pressing one of two keys on a standard keyboard or with mouse clicks on cue values. Data were analyzed with BeGaze 2.3. Fixation detection followed a dispersion threshold of 2° of visual angle and a duration threshold of 100 msec.

Decision Task

In the decision task, participants decided to invite job candidates for an interview or reject them based on information on three attribute dimensions (i.e., cues). The decision task consisted of three phases: a memorization phase, a strategy-learning phase, and a test phase (see Figure 4.1).

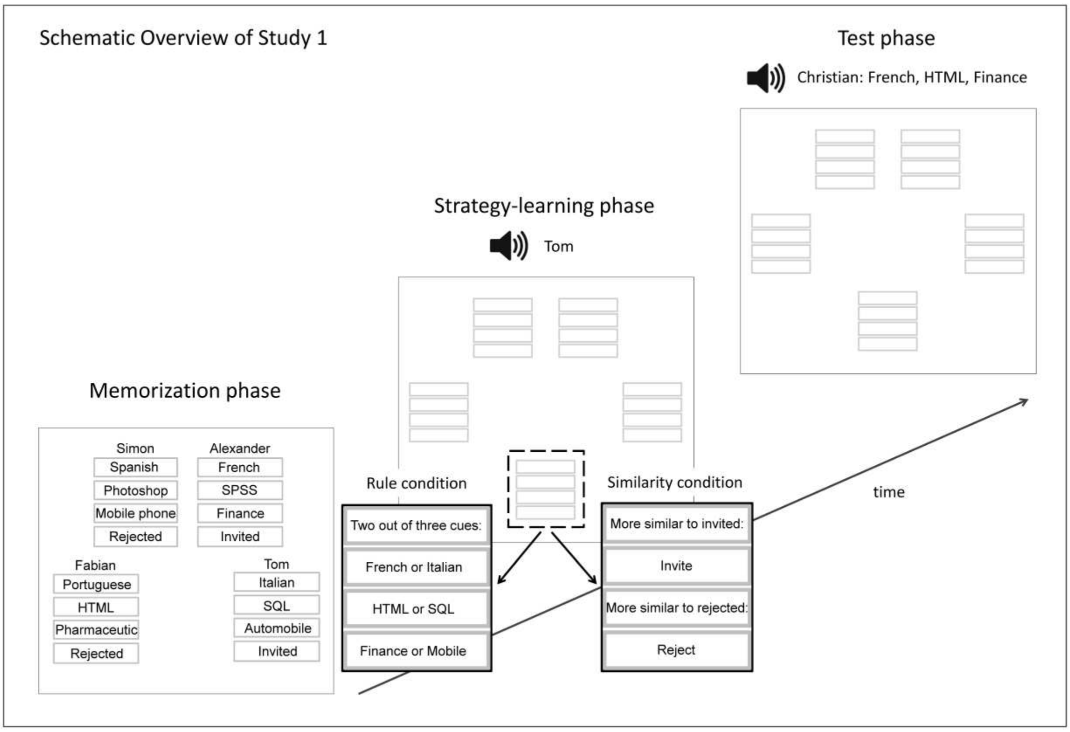

Figure 4.1 Schematic illustration of the three phases in Experiment 1. Participants started with the *memorization phase* in which they had to learn the information about the four learning candidates. The candidates appeared in four rectangles in the upper two-thirds of the screen. Note for the figure we increased the size of the boxes in the memorization phase to enhance readability. The actual distribution of the learning candidates' locations on the screen is reflected in the illustrations of the strategy learning and the test phase. In the study all cue information was written in the same font size. During the *strategy-learning phase* participants decided whether to invite the learning candidates for an interview following either a rule-based or a similarity-based strategy. Participants were told which training candidate they were evaluating in each trial via headphones. During the decision, the rectangles within which the information on the four candidates had appeared were visible but empty. In addition, a bottom rectangle appeared that contained information about the strategy participants should use. During the *test phase*, all rectangles remained visible but did not contain any information. The information about the test candidates participants evaluated was provided via headphones. Original materials were in German.

Memorization phase. During the memorization phase participants memorized information about four male "learning" candidates (candidates used in the memorization and strategy-learning phases). For each learning candidate participants learned the candidate's name, his values on the three cues, and whether he had been invited to an interview. The three cues were knowledge of a foreign language (with cue values French, Italian, Portuguese, and Spanish), possession of computer skills (with cue values HTML, Photoshop, SPSS, and SQL), and previous work experience (with cue values automobile industry, financial sector, mobile phone industry, and pharmaceutical industry). Names of the learning (and test) candidates were taken from an online resource for popular first names (http://www.beliebte-vornamen.de). Each learning candidate had a unique combination of cue values (see Table A.4.1 in the

Appendix). Two of the learning candidates were suitable (i.e., had been invited) and two were unsuitable (i.e., had been rejected). Each of the four learning candidates was associated with a different spatial area located in the upper two-thirds of the screen and at an equal distance from the center of the screen (see Figure 4.1). The candidate's name always appeared on top followed by the cue values and the suitability information (whether the candidate had been invited or rejected). Cue values and suitability information appeared as single words in four rectangles. Positions of learning candidates and the order of the cue values were randomized across participants with the constraint that the two invited learning candidates were always located at the same side of the screen, that is, both were on either the right or the left half of the screen. For a given participant, the order of the cues was the same for all learning candidates (e.g., for the same participant the cue "language" appeared in the second rectangle for all learning candidates).

To learn the names, cue values, and suitability of the four learning candidates, participants first saw all the information about the four learning candidates in the rectangles on the screen and could study it. Once they had studied the information they could click on "continue" and all the information disappeared. Then the name of one of the learning candidates appeared on the screen and participants had to fill in the correct information for this candidate. They could do so by selecting the correct cue value from a table presented at the bottom of the screen. If they selected the correct information it was highlighted in green and appeared in the corresponding rectangle of the learning candidate where it remained visible for the rest of the trial. If they selected incorrect information, it was highlighted in red. In addition, the correct information was highlighted in green and appeared in the rectangle. Participants always filled in cue information for the learning candidates from top to bottom. After reproducing all the information for a learning candidate, the complete information was visible on the screen and was auditorily presented to the participant over the headphones. Then the name of the next learning candidate appeared and the candidate's cue information had to be filled in. After participants filled in the information for all four learning candidates they received feedback about the percentage of correct decisions that had been made and a new cycle began. The sequence in which they had to reproduce the information for the four learning candidates was randomized within a cycle. This procedure was repeated until the participants correctly reproduced the information for all four learning candidates twice. Participant got a bonus of 1 euro if they finished learning within 40 cycles (e.g., each learning applicant would be presented 40 times).

Strategy-learning phase. In the strategy-learning phase, half of the participants were instructed to use a rule to decide if a candidate should be invited and the other half were instructed to decide according to similarity. In the rule condition participants were instructed to invite a job candidate if at least two of the three cues had a positive value. Positive values for each cue were (1) knowledge of French or Italian, (2) knowledge of HTML or SQL, and (3) experience in the financial sector or the mobile phone industry. For instance, according to this rule a candidate should be invited if he speaks French, has knowledge of HTML, and has experience in the automobile industry. However, a candidate should be rejected if he speaks French, has knowledge of SPSS, and is experienced in the automobile industry. Participants in the similarity condition were instructed to invite a candidate if he had more cue values in common with the learning candidates who had been invited than with the learning candidates who had not been invited. Participants were informed that they would need to use the strategy to evaluate the candidates in the test phase and that they could practice using the strategy by relating the strategy's predictions to the cue information for the learning candidates. During the strategy-learning phase a shortened version of the strategy instructions was presented in a fifth spatial area at the bottom of the screen located at the same distance from the center as the areas of the learning candidates (see Figure 4.1). The visual layout of the rectangles in which the strategy instructions were presented was the same as for the information about the learning candidates. With the exception of these different instructions, the strategy-learning phase followed the same procedure in both conditions: The name of one of the learning candidates was presented via headphones and the participants had to decide if he should be invited according to the instructed strategy by retrieving the information about the learning candidate from memory. To make the decision, participants had to press one of two keys on the keyboard. After pressing the key they got visual feedback in the center of the screen about whether their decision was correct or wrong. If the decision was correct a green rectangle appeared in the middle of the screen stating: "This decision is correct. The candidate is invited/rejected." In case of a wrong decision a red rectangle appeared stating "This decision is wrong. The candidate is invited/rejected." In addition, the cue information of the judged learning exemplar became visible in the corresponding spatial area and was auditorily repeated to the participants. Then the next trial started. Strategy learning ended when participants had correctly judged the suitability of all four learning candidates within one cycle.

To check if participants had learned the strategies, we asked them at the end of the strategy-learning phase to reproduce the cue values that would allow them to invite a candidate for an interview. For this all possible cue values were presented onscreen in a table, with the cue values of each cue in one row. Participants had to click on the respective cue values. In the rule condition they had to reproduce the cue values that would allow invitation. In the similarity condition they had to reproduce the cue values of the similar invited learning candidates.

Test phase. To check if participants had understood how to apply the learned strategy to new candidates, they solved one practice trial at the beginning of the test phase, where they had to judge a new candidate, and received feedback about the correctness of their choice. During subsequent trials no feedback was given.

During the test phase, participants judged the suitability of 20 test candidates. Four of them had cue values identical to those of the learning candidates but had different names. The remaining 16 candidates were new candidates who differed in their similarity to the invited and rejected learning candidates. We constructed the test candidates so that they shared n = 0, 1, 2, or 3 cue values with the two invited learning candidates and shared 3−n cue values with the rejected candidates. Thus, a candidate who shared no cue values with the invited learning candidates automatically shared three cue values with the rejected learning candidates, and so on. Details on the task structure can be found in the Appendix, Table A.4.1.

At the beginning of each trial, participants had to fixate on the center of the screen (2 s). Subsequently, the name and cue values of one candidate were presented auditorily over the headphones (6 s) and participants had to decide whether to invite them for an interview by pressing one of two keys on the keyboard (self-paced). While the information was presented participants saw only the empty rectangles in the spatial areas where cue and strategy information had been presented during the memorization and strategy-learning phases. For each correct judgment, participants were paid a bonus of 20 cents.

4.3.2 Results

Performance

Participants memorized the information about the learning candidates rather quickly. On average they reached the learning criterion in 3.2 cycles (SD = 1.3). They also performed well during strategy training: On average, they correctly classified all learning candidates according to the strategy in 1.3 cycles (SD = 0.6). Participants in the two strategy conditions (rule, similarity) were equally fast in memorizing the information, M_{rule} = 3.3, SD = 1.5, M_{sim} = 2.9, SD = 1, $t(45.2)$ = 1.15, p = .26, d = .34, and learning the strategy, M_{rule} = 1.2, SD = 0.5, M_{sim} = 1.4, SD = 0.8, $t(42.4)$ = 1.14, p = .26, d = .36.

In the test phase, we measured accuracy as the percentage of decisions that were in line with the instructed strategy. Accuracy was high and did not differ between the conditions, M_{rule} = 94.3, SD = 8.7 and M_{sim} = 96.5, SD = 5.8, $t(51)$ = 1.12, p = .27, d = .32.

Response times were measured from the beginning of the auditory information presentation during a test trial until participants' response. On average participants in the rule condition, M_{rule} = 9.6 s, SD = 0.6, took as long as participants in the similarity condition, M_{sim} = 9.2 s, SD = 1, $t(51)$ = 1.54, p = .13, d = .43.

Analyses of Fixations

To assess differences in gaze behaviour between the strategy conditions we excluded all trials in which the dwell criterion (at least 60 % of the eye movements were recorded) was not met on the trial level, which led to the exclusion of 70 trials (6.6 % of all trials). We then defined rectangular areas of interest (AOIs) around the location of each learning candidate (exemplar locations) and the instruction location. All AOIs were of the same size (8° by 8° of visual angle). These nonoverlapping AOIs exceeded the exemplar locations by 2.7° of visual angle in the horizontal direction and 1.8° of visual angle in the vertical direction. For each trial, we determined the sum of fixation durations at each of the five AOIs. Fixations on other areas were ignored. *F* values in statistical analyses were Greenhouse–Geisser corrected when necessary. We report the analyses separately for the test candidates who were only similar to the learning candidates and the test candidates who had cue profiles that were identical to the learning candidates' because different memory processes could be involved.

Mean fixation durations for identical test items. In a first step we analyzed only those test items that had an identical cue profile to that of the learning candidates. Following the looking-at-nothing literature, we assumed that if people retrieve exemplars from memory, they should gaze back at the location associated with the learned exemplar when listening to a test item with an identical cue profile. To test this assumption, we calculated the fixation durations for the five AOIs in the trials in which the four identical test candidates were presented. We then tested how long participants gazed on average at the AOI that contained the identical learning exemplars relative to the other four AOIs. For this we coded the exemplar location that had contained the learning candidate with an identical cue profile to that of the test candidate as "match location". The exemplar location that had contained the second invited or rejected learning candidate was coded as "mismatch 1 location". The remaining exemplar locations were coded as mismatch 2 and mismatch 3 from left to right. The location containing the instruction during strategy learning was coded as "instruction location". A mixed analysis of variance (ANOVA) with the within-subject factor exemplar location (match, mismatch 1, mismatch 2, mismatch 3, instruction) and the between-subjects factor strategy condition (rule or similarity) revealed main effects of exemplar location, $F(2.5, 127.1) = 5.36$, $p = .003$, $\eta_p^2 = .10$, and strategy condition, $F(1, 51) = 13.77$, $p = .001$, $\eta_p^2 = .21$, and a significant interaction, indicating that the pattern of eye movements differed between the conditions, $F(2.5, 127.1) = 4.02$, $p = .01$, $\eta_p^2 = .08$. As illustrated in Figure 4.2, participants fixated on the four exemplar locations and the instruction location equally long in the rule condition, $F(2.4, 63.3) = 1.40$, $p = .25$, $\eta_p^2 = .05$. In contrast, in the similarity condition the gaze duration depended on the location, $F(2.4, 60.6) = 5.19$, $p = .005$, $\eta_p^2 = .17$. Participants fixated longer on the match location than on the other exemplar locations (Bonferroni-corrected post hoc contrasts, all *ps* < .03). Participants also fixated longer on the match location than on the instruction location. However, this post-hoc contrast did not reach significance ($p = .22$). Additionally, participants in the similarity condition fixated on the match location longer than participants in the rule condition, $t(32.1) = 4.12$, $p < .001$, $d = 1.45$.

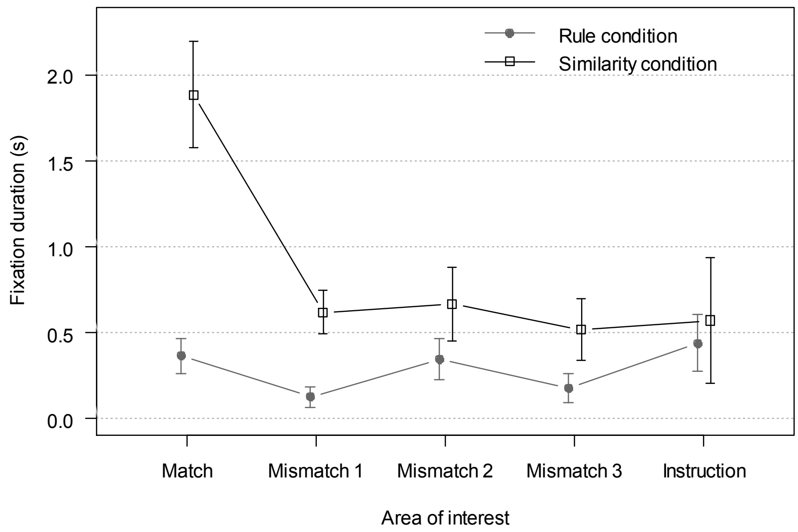

Figure 4.2 Mean duration of fixation on the five areas of interest (AOIs) in the rule as compared to the similarity condition. The first location marks the exemplar location that contained the learning candidate whose cue profile was identical to the respective test candidate's (match). The second, third, and fourth locations refer to the other three exemplar locations (mismatch 1, mismatch 2, mismatch 3). The fifth location refers to the location of the instructions (instruction). Error bars represent one standard error.

Mean fixation durations as a function of item similarity. In a second step we analyzed if the duration of fixation on the exemplar locations differed as a function of the similarity to the learning candidates when evaluating new test candidates who did not have identical cue profiles to those of the learning candidates (see Appendix, Table A.4.1). We first calculated for each participant the mean duration of fixation on the locations of the invited learning candidates, the rejected learning candidates, and the instructions in each trial. Then we calculated for each participant the mean fixation durations for the test candidates who had 0, 1, 2, or 3 cue values in common with the invited learning candidates (and 3, 2, 1, and 0 values in common with the rejected learning candidates, respectively). We then tested if the mean duration of fixation on the locations of the invited and rejected learning candidates varied as a function of similarity (i.e., the number of shared cue values) in the two strategy conditions. For this we ran a mixed ANOVA on the fixation durations with the two within-subject factors similarity (0, 1, 2, 3) and exemplar type (invited vs. rejected) and the between-subjects factor strategy condition (rule vs. similarity). Overall, participants in the similarity condition fixated on the exemplar locations longer than participants in the rule condition, as shown by a main effect of strategy condition, $F(1, 51) = 16.32$, $p < .001$, $\eta_p^2 = .24$. Furthermore, significant interactions between similarity and exemplar type, $F(4.3, 216.7) = 8.36$, $p < .001$, $\eta_p^2 = .14$, and similarity, strategy condition, and exemplar type, $F(4.3, 216.7) = 8.09$, $p < .001$, $\eta_p^2 = .14$, suggested that the effect of similarity differed by strategy condition and exemplar type. As illustrated in Figure 4.3, when we analyzed the two strategy conditions separately we found that in the rule condition, fixation durations did not differ by similarity. Neither the main effect of similarity, $F(3, 78) = 0.92$, $p = .44$, $\eta_p^2 = .03$, nor the interaction between similarity and exemplar type, $F(3.4, 87.4) = 1.14$, $p = .34$, $\eta_p^2 = .04$, was significant. In contrast, in the similarity condition, participants' gaze varied according to similarity, as shown by a significant interaction of similarity and exemplar type, $F(3.3, 82.3) = 10.1$, $p < .001$, $\eta_p^2 = .29$. Indeed, the more cue values a test candidate shared with the invited learning candidates the more participants gazed at invited candidates and the less they gazed at rejected candidates [linear contrast for the invited candidates: $F(1, 25) = 17.84$, $p < .001$, $\eta_p^2 = .42$]. In turn, the more similar the test candidates were to rejected learning candidates, the more participants gazed at rejected candidates and the less they gazed at invited candidates [linear contrast rejected candidates: $F(1, 25) = 19.90$, $p < .001$, $\eta_p^2 = .44$].

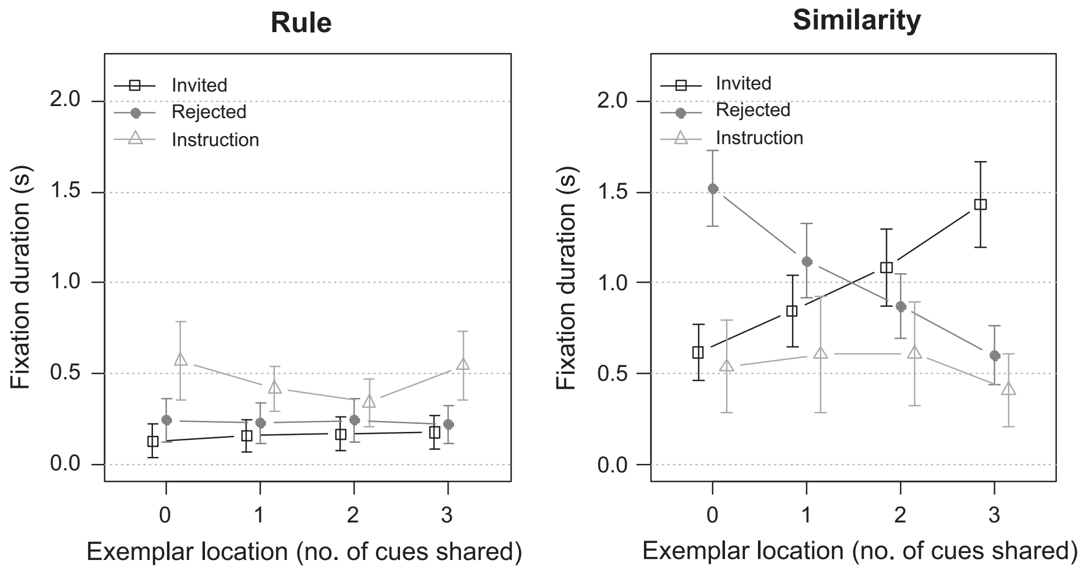

Figure 4.3 Mean duration of fixation for exemplar locations of invited and rejected candidates and the instruction location in the rule condition (left) and the similarity condition (right). Exemplar location refers to the number of shared cue values with invited learning candidates ranging from 0 to 3. The similarity to the rejected candidates is the opposite of the similarity to the invited ones. Thus a similarity to the invited candidates of 0 corresponds to a similarity of 3 to the rejected ones, and so on. Error bars represent one standard error.

4.3.3 Discussion Experiment 1

In Experiment 1 we investigated whether the gaze patterns of participants differ when using a rule-based or a similarity-based decision strategy. Taking into account the finding that when retrieving information from memory people look back at the location where the information previously appeared (e.g., Richardson & Kirkham, 2004; Richardson & Spivey, 2000), we hypothesized that participants' gaze patterns should reflect whether they retrieved the learned exemplars from memory. In line with this hypothesis, we found that when instructed to use a rule, participants did not look back at the locations associated with learning candidates. In contrast, when participants were instructed to make decisions based on the similarity to the learned candidates they looked back at the locations of similar exemplars. These results provide empirical evidence that people retrieve different information from memory when instructed to use a rule- or similarity-based strategy and resonate with the idea that similarity- and rule-based processes differ in how memory representations are accessed (e.g., Bailey, 2005; Hahn & Chater, 1998).

The results are in line with research suggesting that eye movements to locations where information had previously appeared reflect memory retrieval processes (Jahn & Braatz, 2014; Renkewitz & Jahn, 2012) and show that the looking-at-nothing effect not only appears when previously seen exemplars are evaluated but also reflects memory retrieval in response to new information. However, although we found that people looked back at the locations of the previously learned exemplars, we did not find a looking-at-nothing effect for the instruction location in either the rule or the similarity condition. Possibly, the strategy-learning phase was too short to build up a reliable association between the instruction location and episodic memory traces of the strategy. Alternatively, it is possible that the strategy instruction was kept activated during the complete test phase, making retrieval unnecessary.

The goal of the first study was to show that differences in information search in memory can be observed by tracking eye movements during the decision process. We instructed participants to use a rule- or similarity-based strategy — thus ensuring that participants indeed relied on the cognitive process of interest. Based on the first study, however, we cannot tell if the same memory retrieval processes would occur when people spontaneously use a similarity- or rule-based strategy. An explicit instruction to use a strategy induces a deliberate and controlled strategy execution, which could result in different cognitive processes from those that would occur for spontaneous strategy application. In particular, the cognitive processes involved when spontaneously using a similarity-based strategy could differ from a controlled application of similarity, because similarity-based strategies are often thought to be of an implicit and automatic nature (Ashby et al., 1998; Hoffmann et al., 2013; but see Karlsson, Juslin, & Olsson, 2008). In addition, the explicit rule instruction could have impeded retrieval processes that can appear when participants spontaneously rely on a decision rule but not if they deliberately use the rule. Thus, to go one step further and to investigate if the same gaze patterns can be observed when participants spontaneously rely on a rule- or a similarity-based strategy, we conducted a second study in which we did not instruct participants to rely on a specific strategy but aimed to manipulate strategy use implicitly through the task structure.

4.4 Experiment 2

The purpose of Experiment 2 was to test if information retrieval from memory also differs between rule-based and similarity-based decision strategies when the strategy is employed spontaneously. To be able to compare explicit and spontaneous strategy use we investigated the eye movements related to memory processes when strategies are spontaneously employed and when explicit instructions are given to use a specific strategy.

Research in categorization, judgment, and decision-making based on cognitive modeling suggests that the accuracy of strategies and the ease with which a strategy can be employed exert a strong influence on strategy selection (Bröder et al., 2010; Hoffmann et al., 2013; Hoffmann et al., 2014; Pachur & Olsson, 2012; Platzer & Bröder, 2013; Rieskamp & Otto, 2006; von Helversen et al., 2013). Specifically, people have been found to rely on rules as long as rules allow the task to be solved and can be easily applied — which is usually the case with one-dimensional rules. However, when the task cannot be solved by (simple) rules, people frequently switch to a similarity-based strategy (Ashby et al., 1998; Ashby & Maddox, 2005; Erickson et al., 1998; Hoffmann et al., 2014; Juslin et al., 2008; Nosofsky & Palmeri, 1998; Nosofsky, Plameri, & McKinley, 1994). Accordingly, we created two conditions, one in which the decision task could be solved by a simple, one-dimensional rule and the other in which the decision task could only be solved by memorizing the exemplars. In the first condition participants should recognize the rule and rely on a rule-based decision process, whereas in the second condition people should realize that the task cannot be solved by a rule and switch to a similarity-based strategy. We included two test phases. In the first participants could spontaneously choose how to solve the task; in the second phase we instructed them to follow a rule- or similarity-based strategy.

4.4.1 Method

Overall, we used a very similar decision task to that in Experiment 1. Again, participants had to decide whether to invite job candidates for an interview based on three cues. However, to be better able to induce strategy selection through task structure, we increased the number of learning exemplars to eight and adapted the strategy-learning phase to encourage a spontaneous use of the strategies. We recorded participants' eye movements during the two test phases (spontaneous, instructed).

Participants

Fifty-seven people met the validity criterion. We excluded three of them from the analysis, one for not finishing the memorization phase within 1.5 h and two because in the majority of trials less than 60 % of eye movement data was recorded, resulting in a final sample of 54 participants. The majority of the participants were students from the University of Basel (32 female; M_{age} = 27.7 years, range 18–51 years). Participants took part for course credit or financial compensation [16 Swiss francs (CHF) per hour]. In addition, they could earn a bonus depending on their performance in the learning and test phases (*M* = 5.1 CHF). All had normal or corrected-to-normal vision with glasses or contact lenses. Participants were randomly assigned, 26 to the rule condition and 28 to the similarity condition. On average, the experiment lasted 90 min.

Apparatus

The same setup as in Experiment 1 was implemented at the University of Basel. Participants were seated in front of a 22-inch computer screen and the eye tracker system SMI iView RED120 sampled data of the right eye at 120 Hz. Auditory materials were presented via loudspeakers. Fixation detection followed a dispersion threshold of 2° of visual angle and a duration threshold of 100 msec.

Decision Task

We used the same procedure and materials as in Experiment 1 with some adaptations to induce participants to use either a rule or similarity without instructing them to do so. This time the study consisted of four phases: a memorization phase, a strategy-learning phase, and two test phases. In addition, we probed participants' memory of learning candidates' cue values at the end.

Memorization phase. During the memorization phase, participants had to learn the cue values and names of eight learning candidates by heart. We increased the number of learning candidates to be better able to induce using a rule or similarity via the task structure and outcome feedback. In contrast to Experiment 1, where each cue value was unique to a learning candidate, in Experiment 2 each cue value was associated with two learning candidates. The complete task structure can be found in the Appendix, Table A.4.2. As in Experiment 1, each of the eight learning candidates was presented at a different spatial location on the screen that was equidistant from the center and from the neighboring learning candidates (see Figure 4.4). In contrast to Experiment 1, we kept the order of the cues constant for all participants, starting with work experience and following with possession of computer skills and knowledge of a foreign language. In addition, participants did not learn about the suitability of the learning candidate (i.e., whether the candidate was invited to an interview) during the memorization phase. Presentation and test of cue values followed the same procedure as in Experiment 1.

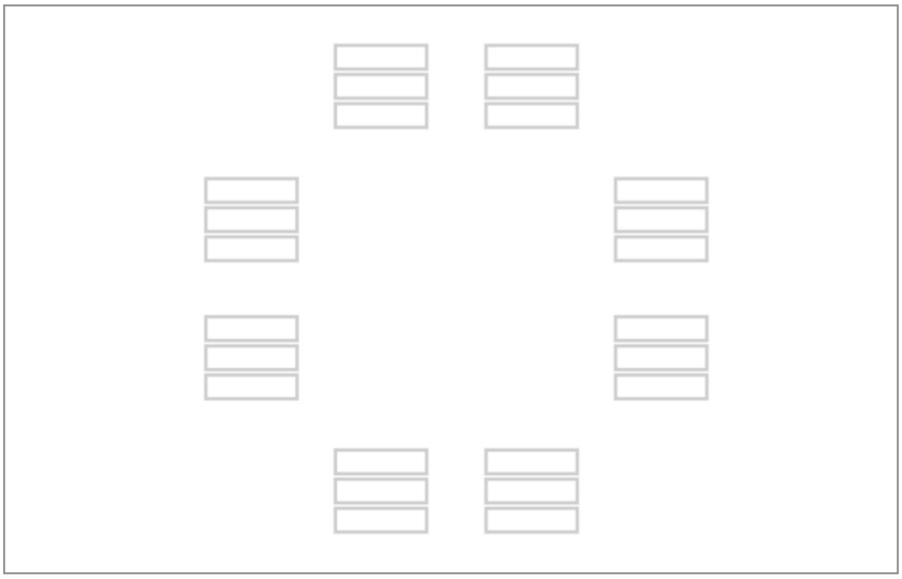

Figure 4.4 Visual layout during both test phases of Experiment 2. During the tests only the empty rectangles were visible.

Strategy-learning phase. During the strategy-learning phase, participants were informed that they had to learn how to decide which candidates should be invited to an interview and that the knowledge they gained during the strategy-learning phase would be necessary to perform the task accurately in the subsequent test phases. Participants could learn to make the decisions based on trial-by-trial outcome feedback. In each trial, participants first fixated on a fixation cross at the center of the screen for 2 s. They then saw a screen containing only the empty rectangles where the learning exemplars had appeared during the memorization phase and heard the name of one of the learning candidates. Then, they had to decide whether they would invite him by pressing one of two keys. After their response, participants got visual feedback on whether they had given the correct response, and the cue information for the judged learning candidate was presented visually and auditorily. The eight learning candidates were presented repeatedly in randomized order with all candidates shown before a new cycle started. Within one cycle the order of the learning candidates was randomized. Strategy learning continued until the participants had correctly judged all learning exemplars in one cycle once or had completed 160 trials (i.e., 20 cycles).

In each condition, four of the learning candidates were invited for an interview and four were rejected. In the rule condition, the task could be solved with a simple rule based on the foreign language cue: A candidate was invited if he spoke French or Italian but not if he spoke Spanish or Portuguese[3]. In the similarity condition, the task could not be solved by a rule but

[3] This rule was rather simple for two reasons: First, it was based on dichotomous cue values of a single cue. Second, the cue values matched with Swiss participants' prior knowledge about languages that are particularly applicable in Switzerland.

only by memorizing the unique cue profile of each learning candidate. Specifically, we selected which of the eight candidates were invited and which were rejected so that every cue value appeared once with an invited and once with a rejected learning candidate (see Appendix, Table A.4.2).

Positions of learning candidates were balanced in two spatial layouts. In both layouts no more than two learning candidates who belonged to the same category (invited or rejected) appeared in adjacent spatial locations. In each strategy condition, half the participants were presented with one spatial layout and the other half with the second layout.

Test Phases 1 and 2. In the test phases, participants had to judge 28 test candidates twice, once in Test Phase 1 and once in Test Phase 2. Eight of them were the learning candidates. Additionally, 20 new candidates were presented who shared 0 to 2 cue values with the learning candidates. As in Experiment 1, participants first saw the fixation cross in the center of the screen (2 s). Then they saw the blank screen (except for the empty rectangles) and listened to the name and cue information of a test candidate. After that, they decided if the candidate should be invited by pressing one of two keys. No feedback was given to the participants.

In Test Phase 1, participants were told to judge the test candidates according to their experience gained in the strategy-learning phase. After Test Phase 1, we asked participants to write down how they solved the judgment task, so we could check if they had indeed used different strategies in the two strategy conditions. In Test Phase 2, participants in the rule condition were instructed to invite participants who knew French or Italian (the same rule that was used to determine feedback in the strategy-learning phase) and participants in the similarity condition were instructed to invite test candidates if they shared more cue values with the invited than with the rejected learning candidates.

Memory test. After completing both test phases, participants were asked to retrieve the cue values of the learning candidates. Participants saw a blank screen containing empty rectangles and filled in cue values of the learning candidates one by one by choosing the appropriate value from a selection that was presented in the center of the screen. For each correct judgment, participants were paid a bonus of 10 cents.

4.4.2 Results

Performance and Strategy Classification

Participants were able to memorize the information on the eight learning candidates rather quickly and did not differ between conditions in the learning cycles they required, M_{rule} = 4.9, *SD* = 2.4, M_{sim} = 4.8, *SD* = 1.9, $t(52) = 0.10$, $p = .92$, $d = .03$. There were only small differences in the amount of practice it took to complete the strategy-learning phase with participants in the rule condition needing somewhat fewer cycles than participants in the similarity condition, M_{rule} = 3.7, *SD* = 1.3, M_{sim} = 5, *SD* = 3.8, $t(52) = 1.82$, $p = .08$, $d = .50$.

In the test phases, we measured accuracy as the percentage of responses that were in line with the strategy that they learned during the strategy-learning phase. Overall, the accuracy was rather high in both conditions, M_{rule} = 91.5, *SD* = 11.5, M_{sim} = 80.4, *SD* = 11.

We then checked if participants had used the intended strategy by classifying them as selecting a similarity- or a rule-based strategy based on their verbal reports after Test Phase 1.[4] Participants were classified into three categories by three independent raters: (1) Simple rule users: Participants mentioned one cue that they used to make a decision, for example, "I concentrated on the cue foreign language. I invited candidates speaking French or Italian. I did not invite candidates speaking Spanish or Portuguese." (2) Complex rule users: Participants mentioned two or more cues, for example, "First I looked up language knowledge. If the candidate spoke French or Italian, I looked up other cues." (3) Similarity users: Participants referred explicitly to using similarity to the learning candidates, for example, "I tried to find the most similar learning candidate and decided [to invite or reject a test candidate] according to this learning candidate." Overall, rater agreement was high. In the cases where the raters disagreed, the case was discussed until agreement was reached. In the rule feedback condition, 10 participants were classified as using a simple rule, 4 as using a complex rule, and 8 as using similarity. In the similarity feedback condition, no participant used a simple rule, 3 participants used a complex rule, and 18 participants used similarity. In four cases in the rule feedback condition and in three cases in the similarity feedback condition participants did not report a strategy or reported problems verbalizing the strategy they used. Similarity is often considered an implicit strategy, which can impair the ability to verbalize it (Ashby et al., 1998). For this reason we included these participants in the similarity user category. To ensure that this did not influence the pattern of results, we additionally ran the analyses without these participants, which yielded the same pattern of results. We excluded four participants in the similarity condition because they reported using different strategies, such as responding by chance. Because participants differed in the strategies they selected in the two conditions, we used strategy classification as an additional factor in the following analyses. We excluded the three participants who were classified as rule users in the similarity condition from the analysis because the low number of rule users in this condition did not allow a statistical comparison. Descriptive statistics for the three rule users in the similarity condition and the four participants who reported using different strategies are included in the Appendix, Table A.4.3.

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[4] The adaptive learning criterion in the strategy-learning phase ensured that participants judged all eight learning candidates in line with the strategy feedback. However, in our task it was not possible to unambiguously determine the strategy a participant used purely based on the participants' decisions. In particular, in the rule condition we cannot rule out based on the decisions that a participant solved the task by using the similarity of the test candidates to the learning candidates on the foreign language cue to make the decision. Thus, we used the verbal reports to determine strategy choices.

We then compared accuracy in the two test phases depending on the strategy condition (rule or similarity) and strategy classification (see Table 4.1). In the rule condition in Test Phase 1, participants using similarity performed worse than participants using a rule, $t(24) = 2.90$, $p = .008$, $d = 1.16$. Participants using similarity in the rule condition improved from Test Phase 1 to 2, $t(11) = 4.85$, $p = .001$, $d = 1.46$, and in Test Phase 2 rule and similarity users were equally accurate, $t(11.83) = 1.22$, $p = .245$, $d = .07$.

Similarity users in the similarity condition were as accurate as similarity users in the rule condition in Test Phase 1, $t(31) = 0.04$, $p = .97$, $d = 0$, but less accurate in Test Phase 2, $t(31) = 3.23$, $p = .003$, $d = .16$. Similarity users in the similarity condition did not differ in terms of accuracy between Test Phase 1 and Test Phase 2, $t(20) = 1.69$, $p = .11$, $d = .38$.

Table 4.1 Means, Standard Deviations, and Sample Size for Response Accuracy (%) in the Two Test Phases.

Test phase	Strategy condition					
	Rule			Similarity		
	M	*SD*	*n*	*M*	*SD*	*n*
1						
Rule users	93	12.4	14	87.7	9	3
Similarity users	77.5	14.9	12	77.7	12	21
2						
Rule users	99	2.2	14	89.9	5.1	3
Similarity users	95.1	10.6	12	82.5	11	21

As in Experiment 1, response times were measured from the beginning of the auditory information presentation until participants' response in a test trial. In Test Phase 1 there were no differences in response times between the rule condition and the similarity condition, M_{rule} = 10.6 s, $SD = 4.3$, M_{sim} = 11.2 s, $SD = 3.6$, $t(28) = 0.53$, $p = .60$, $d = .10$, nor between rule and similarity users, M_{rule} = 10.5 s, $SD = 4.1$, M_{sim} = 11.2 s, $SD = 3.9$, $t(48) = 0.60$, $p = .55$, $d = .17$. In Test Phase 2 participants in the rule condition were faster than participants in the similarity condition, M_{rule} = 8.8 s, $SD = 0.4$, M_{sim} = 10.8 s, $SD = 2.3$, $t(28.8) = 4.52$, $p < .001$, $d = 1.68$. Performance in the memory test at the end of the experiment was very high, with participants remembering almost all information about the learning candidates in both conditions, M_{rule} = 99.2, $SD = 2.1$, M_{sim} = 99.1, $SD = 1.7$, $t(48) = 0.12$, $p = .90$, $d = .03$, independent of the strategy they used.

Analyses of Fixations

To analyze if similarity influenced eye movements we first defined rectangular AOIs around the eight exemplar locations in the same way as in Experiment 1. All AOIs were of the same size (5.5° by 6° of visual angle). These nonoverlapping AOIs exceeded the exemplar locations by approximately 1.5° of visual angle in each direction. As in Experiment 1, we excluded all trials where the dwell criterion was not met (6.5 % of all trials). Then we aggregated durations of fixation on the exemplar locations depending on their similarity to the test candidate in a given trial for each participant. Unlike in Experiment 1, in Experiment 2 more than one exemplar location contained cue values identical to cue values of learning or test candidates. More precisely, for the eight test candidates who were identical to the learning candidates (old test items), one exemplar location contained an identical cue profile, three exemplar locations contained one identical cue, and four exemplar locations contained no identical cues. For the 20 new test candidates (new test items), one or two exemplar locations contained two identical cue values, two to four exemplar locations contained one identical cue, and three or four locations contained no identical cue values. Thus for the old test items, the exemplar locations shared 0, 1, or 3 cue values with the test candidates and for the new items the exemplar locations shared 0, 1, or 2 cue values with the new test items. As in Experiment 1, we analyzed mean duration of fixation on the exemplar locations separately for the old and new items and for Test Phases 1 and 2 (see Figures 4.5 and 4.6). *F* values in statistical analyses were Greenhouse–Geisser corrected when necessary.

Mean fixation durations for old items.

Test Phase 1. In a first step, we analyzed effects of strategy condition and strategy classification on duration of fixation on exemplar locations when judging the old items for Test Phase 1. We assumed that if exemplar retrieval takes place, participants should have fixated on AOIs that contained identical cue values during learning. First, we tested whether mean duration of fixation on exemplar locations differed between participants classified as rule or similarity users in the rule condition of Test Phase 1 (Figure 4.5a). A mixed ANOVA with the within-subject factor exemplar similarity (0, 1, 3) and the between-subjects factor strategy classification (rule or similarity user) revealed that overall, similarity users looked longer at the exemplar locations than rule users, as shown by a main effect of strategy classification, $F(1, 24) = 4.87$, $p = .04$, $\eta_p^2 = .17$. Furthermore, a main effect of exemplar similarity suggests that participants looked longer at the exemplar location associated with the identical learning candidate than at the other exemplar locations, $F(1, 24.8) = 21.74$, $p < .001$, $\eta_p^2 = .48$. Finally, similarity and rule users differed in the degree to which they looked back at the locations of similar learning candidates, as shown by a significant interaction between exemplar similarity and strategy classification, $F(1, 24.8) = 5.05$, $p = .03$, $\eta_p^2 = .17$. In particular, similarity users clearly gazed more often at exemplar locations that were associated with the identical learning candidate than rule users did, $t(24) = 2.29$, $p = .02$, $d = .93$.

Second, we tested whether similarity users in the similarity condition also looked longer at the identical learning candidates (Figure 4.5b). Indeed, an ANOVA for repeated measures testing the factor exemplar similarity revealed a significant effect for exemplar similarity, $F(1, 20.9) = 23.13$, $p < .001$, $\eta_p^2 = .54$, suggesting that participants in the similarity condition looked much more frequently at the location of the identical learning candidate than at the other exemplar locations. Last, a test to determine if similarity users in the rule condition differed from similarity users in the similarity condition showed no difference, as indicated by no main effect for condition, $F(1, 31) = 1.14$, $p = .30$, $\eta_p^2 = .04$, and no interaction between condition and exemplar similarity, $F(1, 32.2) = 0.85$, $p = .43$, $\eta_p^2 = .03$.

Test Phase 2. We repeated the same set of analyses for Test Phase 2. As illustrated in Figure 4.5c, we still found a main effect for exemplar similarity, indicating that participants in the rule condition looked longer at the location of the identical learning candidate than at the other exemplar locations, $F(1, 24.7) = 10.77$, $p < .001$, $\eta_p^2 = .31$. However, in Test Phase 2, participants classified as rule users no longer differed from participants classified as similarity users, as indicated by the lack of a main effect for strategy classification, $F(1, 24) = 0.01$, $p = .91$, $\eta_p^2 = 0$, and no interaction between exemplar similarity and strategy classification, $F(1, 24.7) = 0.76$, $p = .93$, $\eta_p^2 = 0$. This suggests that after being instructed to use a rule, participants changed their strategy according to the instructions. In the similarity condition, the effect of exemplar similarity on fixation durations persisted in Test Phase 2, $F(1, 20.2) = 40.01$, $p < .001$, $\eta_p^2 = .67$ (Figure 4.5d). Last, in Test Phase 2 we found that participants originally classified as similarity users in the rule condition showed a smaller exemplar similarity effect than similarity users in the similarity condition, as shown by a significant main effect for the strategy condition, $F(1, 31) = 11.04$, $p = .002$, $\eta_p^2 = .26$, and an interaction between strategy condition and exemplar similarity, $F(1, 31.5) = 10.73$, $p < .001$, $\eta_p^2 = .26$.

Mean fixation durations for new items.

Test Phase 1. Next, we tested if the effect of exemplar similarity also existed for the new test items that shared 0, 1, or 2 cue values with the learning candidates. As with the old items, we first tested whether similarity users differed from rule users in the rule condition (Figure 4.6a). Similar to what we found for the old items, similarity users looked more at the exemplar locations than did rule users, $F(1, 24) = 5.33$, $p = .03$, $\eta_p^2 = .18$, and overall fixation durations increased with exemplar similarity, $F(1.1, 26.7) = 11.69$, $p < .001$, $\eta_p^2 = .33$. Furthermore, a significant interaction between exemplar similarity and strategy classification indicates that similarity users differed from rule users in the degree to which they looked back at the locations of similar learning candidates, $F(1.1, 26.7) = 6.16$, $p = .02$, $\eta_p^2 = .20$. Whereas exemplar similarity did not play a role for the rule users, $F(1, 13) = 2.34$, $p = .15$, $\eta_p^2 = .15$, similarity users gazed more at the locations of the learning candidates the more cue values these shared with the test candidates, $F(1, 11) = 9.19$, $p = .01$, $\eta_p^2 = .45$.

In the same vein, we found that similarity users in the similarity condition also looked more at the exemplar locations of similar learning candidates than at the locations of learning candidates that had different cue values, $F(1.3, 26.6) = 13.01$, $p < .001$, $\eta_p^2 = .39$ (Figure 4.6b).

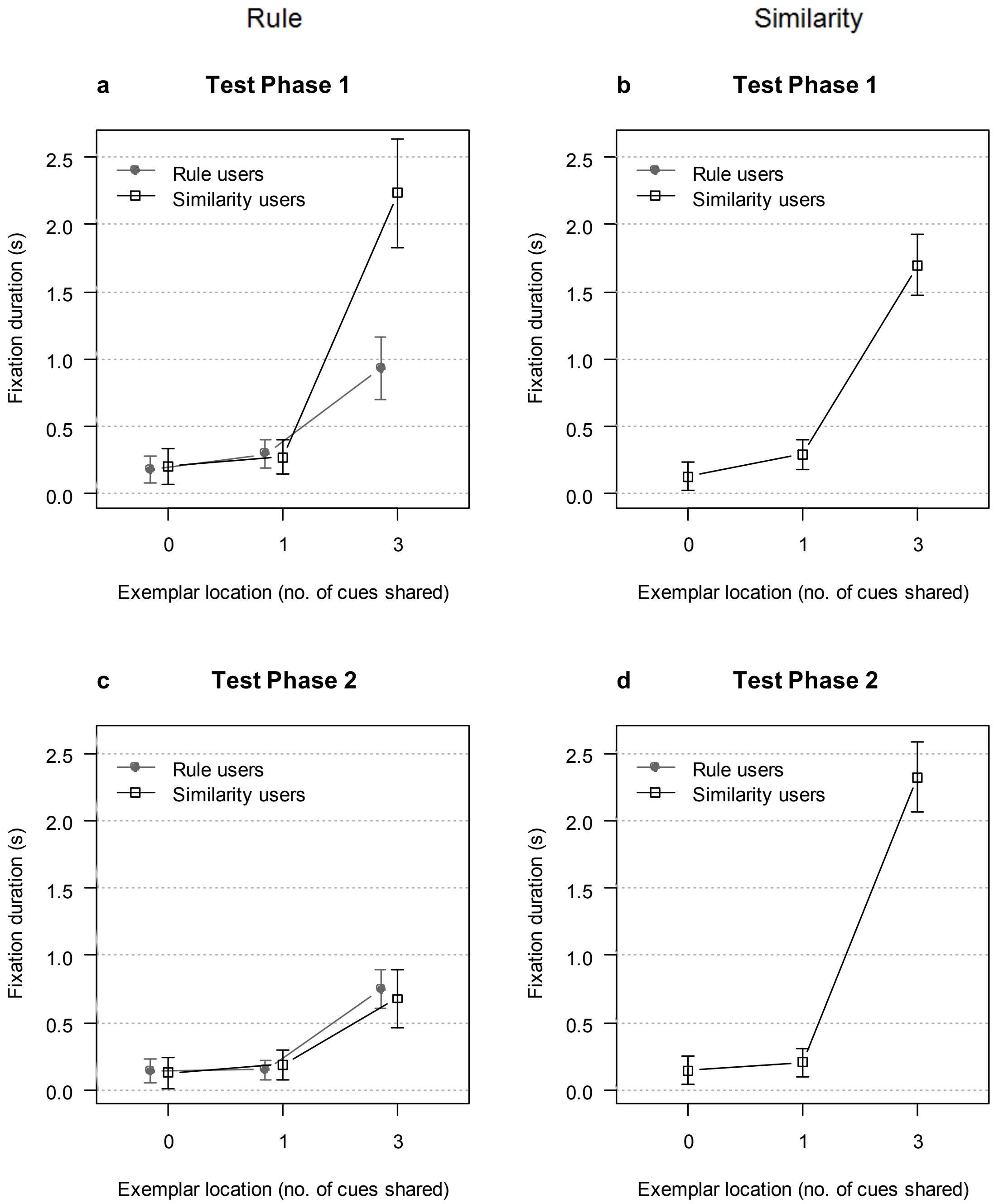

Figure 4.5 Mean duration of fixation on exemplar locations sharing 0 to 3 cue values with old test items for the rule condition (a, c) and the similarity condition (b, d) by strategy classification (rule user, similarity user) and test phase (Test Phase 1 spontaneous use: a, b; Test Phase 2 strategy instruction: c, d). Error bars show standard errors.

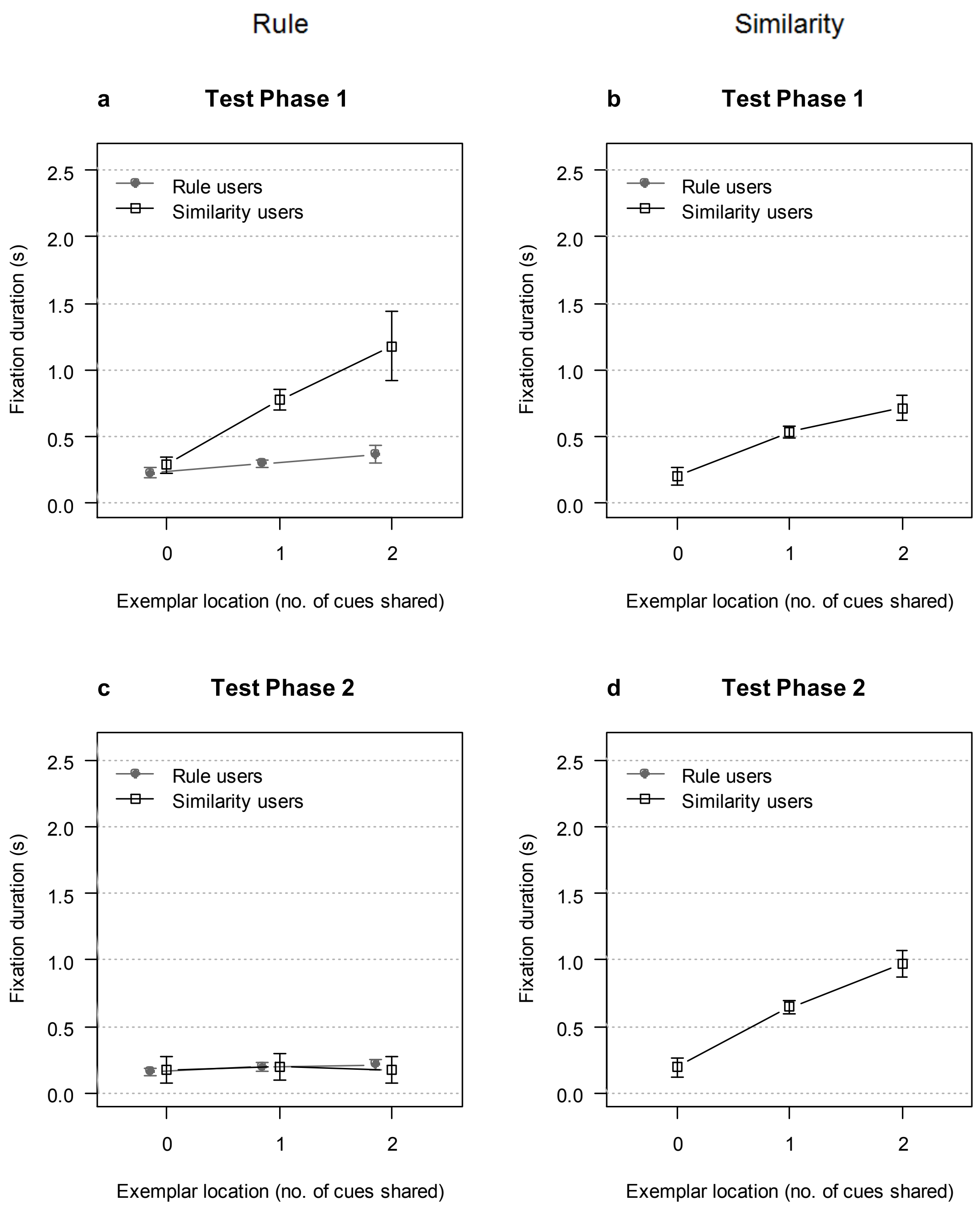

Figure 4.6 Mean duration of fixation on exemplar locations sharing 0 to 2 cue values with new test items for the rule condition (a, c) and the similarity condition (b, d) by strategy classification (rule user, similarity user) and test phase (Test Phase 1 spontaneous use: a, b; Test Phase 2 strategy instruction: c, d). Error bars show standard errors.

Similarity users in the similarity condition and similarity users in the rule condition did not differ significantly from each other, as indicated by the lack of a main effect for condition, $F(1, 31) = 2.10$, $p = .16$, $\eta_p^2 = .06$, and a nonsignificant interaction between condition and exemplar similarity, $F(1.2, 37.4) = 1.63$, $p = .21$, $\eta_p^2 = .05$.

Test Phase 2. We repeated the same analyses for Test Phase 2. As shown in Figure 4.6c, we did not find an effect for exemplar similarity, $F(2, 48) = 0.81$, $p = .45$, $\eta_p^2 = .03$, or strategy classification, $F(1, 24) = 0.24$, $p = .88$, $\eta_p^2 = .0$, nor an interaction between these two factors in the rule condition, $F(2, 48) = 0.51$, $p = .60$, $\eta_p^2 = .02$. Participants almost did not look at exemplar locations, regardless of their classification as rule or similarity user. In contrast, we still found an effect of exemplar similarity in the similarity condition, $F(1.2, 23.0) = 26.10$, $p < .001$, $\eta_p^2 = .57$ (Figure 4.6d).

Last, we compared participants classified as similarity users in the rule and similarity conditions. Whereas similarity users in the similarity condition looked more at the exemplar locations of similar learning candidates than the locations of learning exemplars with different cue values, similarity users in the rule condition did not look back at the exemplar locations of similar learning candidates. This gaze pattern is confirmed by the results of a mixed ANOVA that showed a main effect for the factor strategy condition, $F(1, 31) = 12.48$, $p = .001$, $\eta_p^2 = .29$, and a significant interaction between the factors exemplar similarity and strategy condition, $F(1.3, 38.0) = 13.99$, $p < .001$, $\eta_p^2 = .31$.

4.4.3 Discussion Experiment 2

Overall, we found a similar pattern of results to that in Experiment 1. Participants using a similarity-based strategy showed a strong effect of similarity on eye movements. They looked more frequently at locations where identical but also where similar exemplars to the candidate under consideration had been presented. This was the case when participants were not instructed to use a specific strategy as well as when instructed to rely on similarity. Furthermore, the same effect appeared for all participants classified as using similarity, independent of whether they had received feedback inducing a similarity-based strategy.

As in Experiment 1 participants classified as using a rule or instructed to use a rule did not look back at the locations of similar exemplars. However, in contrast to Experiment 1, we found a memory effect when the same candidates appeared during test that had been studied previously. Here we found that even participants instructed to use a rule looked more frequently at the location where the specific candidate had appeared before. This indicates that when it was not necessary to use a rule because a specific candidate was recognized, participants relied on memory retrieval, but not when new candidates were evaluated. Possibly this effect did not appear in Experiment 1 because there the “identical” candidates appeared with new names during test, whereas they had the same names in Experiment 2, which could have induced recognition regardless of the strategy they used.

We were only partly able to induce participants to use a rule- or similarity-based strategy. Participants' self-reports showed that also in the rule feedback condition a considerable number of participants used similarity. These results are in contrast to studies showing that usually people prefer simple rules to similarity (Ashby & Maddox, 2005; Erickson et al., 1998; Hoffmann et al., 2014; Nosofsky et al., 1994). However, our studies differed from these experiments, because usually the information about the candidate does not need to be retrieved from memory. In contrast, in our task participants had to learn the rule while retrieving the cue values from memory. Indeed, Platzer and Bröder (2013) showed that in memory-based decisions people more frequently rely on similarity – in particular if the cue polarity (i.e., which cue value is associated with a positive outcome) is not known. In our task, learning about the direction of a cue was even more complex because every cue could take on four values compared to two cue values in the experiment by Platzer and Bröder (2013).

In the analysis, we classified participants based on verbal descriptions of the strategies they used. The ability to verbalize is frequently considered a feature of rule application, whereas similarity-based strategies are often considered implicit and thus less accessible to deliberate reporting. Thus, similarity users might be less able to accurately report the strategy they used (Ashby et al., 1998; Ashby & Maddox, 2005). Indeed, participants who reported using a rule were easily classified and rater agreement was very high, reaching 100 % for participants classified as using a simple rule. The majority of similarity users could be clearly classified as using similarity based on their description, but because similarity might be difficult to verbalize we included participants who were unable to verbalize the strategy they used in the similarity user category. However, we cannot rule out that these participants actually followed a different strategy, combined a rule-based and a similarity-based strategy, or switched strategies between trials. Overall, our results suggest that the gaze pattern of these participants reflects retrieval processes caused by similarity. Future research, however, should investigate if there are differences between people who rely on a single strategy and those who use multiple strategies as well as possible differences between participants who have insight into the strategies they used and participants who do not. Furthermore, researchers disagree on the degree to which self-reports reflect people's actual cognitive processes versus only general beliefs about how they made a decision (e.g., Harries, Evans, & Dennis, 2000; Lagnado, Newll, Kahan, & Shanks, 2006). This suggests that future research should use additional methods such as cognitive modeling to corroborate our findings.

4.5 General Discussion

When making everyday decisions from memory people can apply abstract rules that process the available information for a decision or they can make a decision according to similar decision situations encountered in the past (Ashby et al., 1998; Erickson et al., 1998; Juslin & Persson, 2002; Nosofsky et al., 1994; Platzer & Bröder, 2013). Although this distinction is intuitively appealing it proves hard to separate on a process level. One reason is that the two processes are conceptually difficult to distinguish (Hahn & Chater, 1998; Markman et al., 2005; Pothos, 2005). Another problem is that hardly any tools exist that can trace memory processes during higher-level mental processes that are not intrusive and can measure the ongoing memory processes online (e.g., Bröder, 2000; Peterson & Beck, 2011).

In two studies we explored memory processes during similarity- versus rule-based retrieval processes using a recently developed method based on the measurement of eye movements (Jahn & Braatz, 2014; Renkewitz & Jahn, 2012). We found that participants using a similarity-based strategy differed in their eye movements from participants using a rule-based strategy: Whereas participants using similarity fixated on spatial locations that were associated with exemplars during learning, participants using a rule did not look back at the locations of the previously learned exemplars. This was the case when applying a complex rule based on multiple cues (Experiment 1) as well as a simple one-dimensional rule (Experiment 2), when applying similarity based on matches to four exemplars with unique cue values (Experiment 1) as well as when applying similarity to eight exemplars with each cue value associated with two exemplars (Experiment 2), and when instructed to use a strategy (Experiment 1) as well as when selecting a strategy spontaneously (Experiment 2). In sum, these results provide robust evidence that participants using a similarity-based strategy retrieved exemplar information from memory, whereas participants who used a rule to arrive at a decision did not retrieve exemplar information from memory.

4.5.1 Using Eye Movements to Study Memory Retrieval in Decision-making

In both studies we found that people showed differences in eye movements depending on the retrieval demands of the decision strategy they employed. These results are in line with the idea that eye movements to associated spatial locations can be seen as direct evidence for memory retrieval, and the results dovetail with an ever-growing number of papers showing that when retrieving information from memory, people gaze back at spatial locations that have been associated with the to-be-retrieved information during encoding (e.g., Hoover & Richardson, 2008; Jahn & Braatz, 2014; Renkewitz & Jahn, 2012; Richardson & Kirkham, 2004; Richardson & Spivey, 2000).

In addition, our findings support the idea that eye movements do not reflect an automatic response that is executed upon listening to a statement probing associated spatial information, but rather a strategy-based retrieval process (Jahn & Braatz, 2014; Renkewitz & Jahn, 2012). If eye movements are the result of an automatic link between perception and retrieval, rule users should have shown the same pattern of eye movements as similarity users, because listening to cue information should have automatically activated the episodic memory trace and triggered eye movements back to the associated spatial locations. Instead, rule user did not look back at these locations. This view is in line with findings in diagnostic reasoning where gaze behaviour has been shown to reflect the activation status of a hypothesis in memory (Jahn & Braatz, 2014). Here, we demonstrated that this research can be extended to study how eye movements reflect the memory processes involved in similarity- and rule-based decision and judgment processes.

In our study people's eye movements were free and unrestricted. Recent research, however, suggests that triggering the eyes to move to a specific location during retrieval can enhance the retrieval of the information associated with that location (Johansson et al., 2012; Johansson & Johansson, 2014; Laeng et al., 2014; Scholz et al., 2014). Similarly, manipulating the salience of cues (Platzer & Bröder, 2012) and guiding the eyes toward valid and invalid cue information (Platzer et al., 2014) have been shown to influence the probability with which the cues are retrieved from memory and the resulting decision strategy. This suggests that guiding eye movements to locations could be a subtle way to alter the decision-making process, even if these locations no longer contain any information. However, with unrestricted eye movements, enhanced retrieval accuracy due to eye movements to associated but emptied spatial locations is unlikely (cf. Richardson et al., 2009; Richardson & Kirkham, 2004).

4.5.2 Memory Retrieval in Rule-based and Similarity-based Decisions

We found in both studies that people using a rule did not look back at the locations of previously learned exemplars, but people using a similarity-based strategy did, independent of the complexity of the task structure and if the strategy was instructed or spontaneously used. This suggests that similarity-based and rule-based decisions rely on different memory processes. These results are in line with the assumptions of Hahn and Chater (1998; see also Bailey, 2005), who proposed that the core difference between rule and similarity lies not in the nature of the mental representations that are built, but in the way memory representations of stored information are matched with a novel object. Whereas similarity users make a decision by matching the object under consideration against the stored exemplars, rule users compare the object against the conditions for choosing a specific option specified by the rule. Correspondingly, we found that only participants using similarity returned their gaze to the locations associated with exemplars, even though we made sure that rule and similarity users had the same information available in memory: Similarity and rule users received the same cue information about job candidates and we ensured that they were equally able to retrieve this information throughout the decision-making phase. Furthermore, a memory check at the end of Experiment 2 showed that participants remembered almost all the cue information and that there was no difference in recall accuracy between users of similarity- and rule-based strategies.

Eye movements suggest that for participants using a similarity-based strategy, memory retrieval was a direct function of similarity with similar exemplars being fixated on more than nonsimilar exemplars. This idea is in line with multiple-trace models of memory such as the MINERVA model, which assumes that recall is a function of similarity to the object under consideration and the frequency and recency with which it was encountered during learning (Hintzman, 1988; Nosofsky & Palmeri, 1997). In our study, frequency and recency were the same for all exemplars, leaving the effect of similarity. However, our results suggest that using eye movements to trace memory retrieval could be a promising avenue to investigate how frequency and recency interact with similarity when retrieving information.

Overall, the differences between rule and similarity users were somewhat more pronounced when they followed instruction than when we compared participants who were classified based on their verbal reports. This suggests that the memory processes involved in an explicit and deliberate application of a strategy are comparable to the processes triggered by spontaneous use. However, a considerable number of participants were unable to verbalize the strategy they used, and it is possible that this is the result of using a combination of similarity and rule-based processes (e.g., Brooks & Hannah, 2006; Hahn et al., 2010; von Helversen, Herzog, & Rieskamp, 2014). Here, making retrieval processes visible by tracing eye movements during the decision phase could be a valuable tool to analyze the memory processes involved in spontaneous decisions.

4.6 Conclusion

By observing eye movements while people performed memory-based decisions using a similarity-based or a rule-based strategy, we showed that the two strategies involve different memory processes. Although similarity and rule users had built the same memory representations, they differed in how these representations were accessed when making a decision. Whereas similarity users retrieved information about similar exemplars, rule users did not—providing empirical evidence that the two processes can be disentangled on the process level. Our results show that observing peoples' eye movements to "nothing" can make cognitive processes visible that otherwise would be hidden from sight.

4.7 Appendix

Table A.4.1 Item Structure in Experiment 1

Test candidate no.	Cue 1: Language skills	Cue 2: Computer skills	Cue 3: Work experience	Exemplar location (no. cues shared)	Strategy prediction	
					Rule	Similarity
1	*Italian*	*SQL*	*Automobile*	*3*	*Invited*	*Invited*
2	*French*	*SPSS*	*Finance*	*3*	*Invited*	*Invited*
3	French	SQL	Finance	3	Invited	Invited
4	Italian	SPSS	Finance	3	Invited	Invited
5	French	SPSS	Mobile phone	2	Invited	Invited
6	Italian	HTML	Automobile	2	Invited	Invited
7	Portuguese	HTML	Finance	1	Invited	Rejected
8	French	Photoshop	Mobile phone	1	Invited	Rejected
9	Spanish	HTML	Mobile phone	0	Invited	Rejected
10	Portuguese	HTML	Mobile phone	0	Invited	Rejected
11	*Portuguese*	*HTML*	*Pharmaceutical*	*0*	*Rejected*	*Rejected*
12	*Spanish*	*Photoshop*	*Mobile phone*	*0*	*Rejected*	*Rejected*
13	Spanish	Photoshop	Pharmaceutical	0	Rejected	Rejected
14	Portuguese	Photoshop	Mobile phone	0	Rejected	Rejected
15	Portuguese	HTML	Automobile	1	Rejected	Rejected
16	Spanish	SPSS	Mobile phone	1	Rejected	Rejected
17	Spanish	SQL	Automobile	2	Rejected	Invited
18	Italian	Photoshop	Automobile	2	Rejected	Invited
19	French	SPSS	Automobile	3	Rejected	Invited
20	Italian	SPSS	Automobile	3	Rejected	Invited

Note. Exemplar location indicates number of corresponding cue values with the invited learning candidates. Strategy prediction indicates if a test candidate was invited or rejected according to the rule or similarity instruction. Italic type denotes test candidates who had cue patterns identical to those of the learning candidates (identical test items). Test candidates 1 and 2 correspond with invited learning candidates and candidates 11 and 12 with rejected learning candidates. All remaining test candidates varied in their similarity to the invited learning candidates (new test items).

Table A.4.2 Item Structure in Experiment 2

Test candidate no.	Cue 1: Language skills	Cue 2: Computer skills	Cue 3: Work experience	Strategy prediction	
				Rule	Similarity
1	French	SPSS	Automobile	Invited	Rejected
2	French	SQL	Mobile phone	Invited	Rejected
3	*French*	*SPSS*	*Mobile phone*	*Invited*	*Rejected*
4	French	Photoshop	Mobile phone	Invited	Invited
5	French	SPSS	Financial	Invited	Invited
6	French	HTML	Financial	Invited	Ambiguous
7	*French*	*Photoshop*	*Financial*	*Invited*	*Invited*
8	*Italian*	*SQL*	*Automobile*	*Invited*	*Invited*
9	Italian	SPSS	Automobile	Invited	Ambiguous
10	Italian	HTML	Automobile	Invited	Invited
11	Italian	SQL	Pharmaceutical	Invited	Invited
12	*Italian*	*HTML*	*Pharmaceutical*	*Invited*	*Rejected*
13	Italian	Photoshop	Pharmaceutical	Invited	Rejected
14	Italian	HTML	Financial	Invited	Rejected
15	Spanish	SPSS	Automobile	Rejected	Ambiguous
16	Spanish	SQL	Pharmaceutical	Rejected	Invited
17	*Spanish*	*SPSS*	*Pharmaceutical*	*Rejected*	*Invited*
18	Spanish	Photoshop	Pharmaceutical	Rejected	Ambiguous
19	Spanish	SQL	Mobile phone	Rejected	Rejected
20	*Spanish*	*SQL*	*Financial*	*Rejected*	*Rejected*
21	Spanish	SPSS	Financial	Rejected	Invited
22	Portuguese	HTML	Automobile	Rejected	Invited
23	*Portuguese*	*Photoshop*	*Automobile*	*Rejected*	*Rejected*
24	Portuguese	Photoshop	Pharmaceutical	Rejected	Rejected
25	Portuguese	SQL	Mobile phone	Rejected	Ambiguous
26	*Portuguese*	*HTML*	*Mobile phone*	*Rejected*	*Invited*
27	Portuguese	Photoshop	Mobile phone	Rejected	Invited
28	Portuguese	HTML	Financial	Rejected	Ambiguous

Note. Strategy prediction indicates if a test candidate was invited according to the received strategy feedback (rule or similarity). According to the similarity feedback, six test candidates were equally similar to an invited and a rejected learning candidate and were classified as ambiguous. Italics denote test candidates who corresponded in their cue patterns with the eight learning candidates (old items). According to the rule feedback, candidates with the numbers 3, 7, 8, and 12 were invited and candidates number 17, 20, 23, and 26 were rejected. According to the similarity feedback, candidates number 7, 8, 17, and 26 were invited and candidates number 3, 12, 20, and 23 were rejected. All other test candidates varied in their similarity with the learning candidates (new items).

Table A.4.3 Means and Standard Deviations for Response Accuracy (%), Response Times (seconds) and Fixation Durations (seconds) on Exemplar Locations for Old and New Test Items and Test Phases 1 and 2 for the Seven Participants in the Similarity Condition in Experiment 2 Who Either Used a Rule (Participants 1–3) or Reported Using a Different Strategy (Participants 4–7)

Participant no.	Response accuracy		Response time		Exemplar location (no. cues shared)					
					0		1		2/3	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
					Old items					
Test Phase 1										
1	100	0	9.2	1.2	0.2	0.2	0.2	0.2	1.3	2.4
2	86	38	22.4	14.9	0.2	0.2	1.1	1	3.4	3.8
3	100	0	9	0.6	0	0.1	0	0.1	0.1	0.2
4	75	46	9.3	1.7	0	0	0	0.1	3.3	1.8
5	100	0	9.2	1.3	0	0	0	0.1	0	0
6	88	35	10.2	3.7	0.1	0.2	0.8	1.1	2.3	1.8
7	100	0	9	0.4	0.2	0.3	0.1	0.2	0.3	0.7
Test Phase 2										
1	100	0	9.1	1	0.2	0.2	0.3	0.2	1.9	1.6
2	67	52	12.5	8.8	0.3	0.4	0.6	0.6	2.6	4.7
3	100	0	8.4	0.3	0.1	0.2	0.2	0.5	0	0
4	63	52	8.5	0.5	0.1	0.1	0	0.1	3.9	0.7
5	100	0	9.1	1	0.2	0.6	0.2	0.4	1.6	3.7
6	100	0	10.1	2.1	0.1	0.2	0.3	0.3	5	1.8
7	88	35	8.8	0.7	0.5	0.5	0.5	0.5	0.9	1.7
					New items					
Test Phase 1										
1	90	31	10.6	2.3	0.2	0.3	0.4	0.5	0.6	1.1
2	73	46	27.8	16.4	0.7	1.3	1.2	1.4	1.1	1.6
3	90	31	11.9	2.9	0.4	0.4	0.4	0.5	0.4	0.6
4	75	44	8.8	0.5	0.1	0.1	0.3	0.4	0.3	0.8
5	80	41	15.9	6	0	0.2	0	0.1	0.2	0.8
6	75	44	11.6	3	0.4	0.6	0.8	1	0.7	1.1
7	70	47	9.1	0.7	0.1	0.3	0.2	0.4	0.2	0.6
Test Phase 2										
1	90	31	12.7	6.0	0.3	0.4	0.7	0.7	1.2	0.9
2	89	32	13	8.4	0.2	0.2	0.8	1.2	1.2	1.4
3	90	31	10.6	2.5	0	0	0	0.1	0.1	0.3
4	75	44	10.5	1.7	0.2	0.2	0.9	0.6	0.9	1
5	90	31	22.7	17.5	0.1	0.1	1.2	2.9	1.4	4.8
6	65	49	13	5	0.4	0.6	1.5	0.9	1.8	1.6
7	70	47	11.1	1.9	0.4	0.4	0.4	0.5	0.4	0.6

Note. Old items shared 0, 1, and 3 cue vales with exemplars and new items shared 0, 1, and 2 cue values with exemplars.

5 Eye Movements and the Development of Explanations over Time

5.1 Abstract

Memory indexing is an eye tracking method that affords rich time course information about memory-based cognitive processing during complex tasks such as reasoning, thinking, and decision-making. We apply memory indexing to reveal symptom processing in sequential diagnostic reasoning, in which multiple pieces of information are evaluated to find a probable explanation for observed symptoms. Participants first learned information about causes and symptoms presented in spatial frames. Gaze allocation on emptied spatial frames during symptom processing and during the diagnostic response reflected the subjective status of hypotheses held in memory and the preferred interpretation of ambiguous symptoms. All symptom sequences supported multiple diagnoses and thus, each diagnosis was chosen under uncertainty. Memory indexing traced how the diagnostic decision developed and it revealed instances of hypothesis change and biases in symptom processing that explain the observed order effects. Memory indexing thus provided direct online evidence for coherence maximization in processing ambiguous information.

Keywords: eye movements, process tracing, memory indexing, diagnostic reasoning, belief updating

5.2 Introduction

In diagnostic reasoning the task is to find a probable explanation for a set of observations (Johnson & Krems, 2001; Patel, Arocha, & Zhang, 2005). For example, a physician has to find the most likely cause for a patient's symptoms. Usually, symptoms are reported sequentially and have to be evaluated based on knowledge stored in long-term memory (Thomas, Dougherty, Sprenger, & Harbison, 2008). Symptom information can be sufficient to determine a single explanation. But often, the available information supports more than one hypothesis (McKenzie, 1998) and thus is ambiguous. An ambiguous case elicits differing final diagnoses even though early observed symptoms may strongly suggest a certain hypothesis. A diagnostician may stay with an initial hypothesis or change to an alternative. In the present study, we apply eye tracking in a manner suitable for process tracing of memory-based reasoning and decision-making (memory indexing) to reveal coherence maximizing in symptom processing leading to one or the other diagnosis for ambiguous cases.

If a symptom sequence supports multiple hypotheses (i.e. an ambiguous symptom sequence) and hypotheses are supported to differing degrees, the hypothesis receiving the strongest support is most likely chosen. However, an objectively less supported hypothesis may be chosen instead because a diagnosis reflects the subjective evaluation of symptoms (Slovic & Lichtenstein, 1971). For instance, the *order* in which symptoms are presented affects symptom evaluation in a systematic manner (Baumann et al., 2010; Bergus, Chapman, Levy, Ely, & Oppliger, 1998; Hogarth & Einhorn, 1992; Trueblood & Busemeyer, 2011). Recent research suggests that symptom processing in sequential diagnostic reasoning with ambiguous symptom sets is often *biased* towards the hypothesis that is supported by symptoms presented early in the symptom sequence (Busemeyer & Townsend, 1993; Lange, Thomas, & Davelaar, 2012; Rebitschek et al., 2012; Weber, Böckenholt, Hilton, & Wallace, 1993). This is especially true when participants are probed only after they have received all symptom information (end of sequence response mode, Hogarth & Einhorn, 1992). These findings on *diagnosis momentum* (Croskerry, 2003), which constitute instances of the more general phenomenon of confirmation bias (Nickerson, 1998), can be interpreted as a reasoners' tendency to strive for a coherent interpretation of presented information and to distort information to increase coherence (Kostopoulou, Russo, Keenan, Delaney, & Douiri, 2012; Russo, Medvec, & Meloy, 1996; Wang, Johnson, & Zhang, 2006). Maximizing coherence more often favors the initially leading hypothesis, but it can also strengthen an alternative after a hypothesis change. Such a change is likely if clearly stronger evidence for an alternative hypothesis has accumulated.

Biased symptom processing influenced by the order of symptoms is most clearly exemplified with maximally ambiguous cases that contain equal support for two hypotheses. The probability that a patient suffers from a certain disease given equal support for this and another disease (and equal base rates) is .5 and constitutes maximal ambiguity. Deviations of diagnosis proportions from .5 indicate biased symptom processing. The same set of symptoms presented in one order may favor one diagnosis and presented in a different order may favor the alternative.

Another special case of ambiguity results if two alternatives are supported by the same number of symptoms, but for one hypothesis the supporting symptoms are more diagnostic whereas for the other hypothesis the supporting symptoms are more diverse. Symptoms are maximally diagnostic for a hypothesized cause if they are only linked to this cause. For example, if eyes symptoms support only one hypothesis then two symptoms that are derived from the eyes symptom class (e.g., “eyelid swelling” and “lacrimation”) are maximally diagnostic. However, these symptoms are not diverse. Two symptoms are diverse if they cover two different symptom classes that are linked to a hypothesis (e.g., “lacrimation” and “cough” covering the symptom classes “eyes” and “respiration”). Diverse symptoms can provide stronger support than non-diverse symptoms. This has been explained, for example, by similarity coverage (Osherson, Smith, Wilkie, López, & Shafir, 1990) and causal diversity (Kim & Keil, 2003; Kim, Yopchick, & de Kwaadsteniet, 2008). Diversity and diagnosticity are independent because diverse symptoms may also be linked to other hypotheses and thus be less diagnostic. Ambiguous symptom sets consisting of equal numbers of maximally diagnostic but non-diverse symptoms supporting one hypothesis and less diagnostic but diverse symptoms supporting another hypothesis thus pit diagnosticity and diversity against each other.

The three types of ambiguous symptom sets – superior support for one hypothesis, equal support, and diagnosticity vs. diversity – are all interesting to study with process tracing. For symptom sets with superior support process data clarify how coherence maximizing can result in choosing the less supported diagnosis. With equal support process data reveal how coherence maximizing pushes one of two competing hypotheses. And for diagnosticity vs. diversity process tracing reveals, for instance, how much a second symptom from a maximally diagnostic symptom class increases the status of the respective hypothesis. Diagnostic reasoning as a memory-based task poses challenges for process tracing. But recently, a method has been developed that allows tracing the status of multiple hypotheses in parallel and indicates coherence maximizing in symptom processing.

Process measures were thought to be not applicable to study memory-based processes, because cognition was thought to proceed without accompanying actions towards the environment. However, recent research on the so-called “looking-at-nothing” phenomenon and the “visual-world” paradigm has proven that eye movements are applicable to study memory retrieval (e.g., Ferreira et al., 2008; Richardson & Kirkham, 2004) and language processing (Allopenna et al., 1998; Altmann & Kamide, 2009; Tanenhaus et al., 1995). Taking these results a step further, “memory indexing” has been developed as a process measure to study higher-level cognitive tasks (Jahn & Braatz, 2014; Renkewitz & Jahn, 2010, 2012). In a memory indexing study, participants first learn information that is presented at different spatial locations on a computer screen. During a subsequent decision or reasoning phase, the spatial locations that contained information during learning are empty and eye movements are recorded. In decision-making, eye movements matched spontaneously applied decision heuristics (Renkewitz & Jahn, 2012). Inferring memory-based processing by observing eye movements is possible, because when processing information from the outside world, human cognition combines visual and auditory perceptual input with conceptual knowledge resulting in mental representations stored in episodic memory traces. Reactivation of parts of such a representation reestablishes a spatial index that leads the gaze back to spatial locations that were associated with the retrieved context (Huettig et al., 2011; Theeuwes et al., 2009). A spatial index can be linked to episodic memories (Hoover & Richardson, 2008; Richardson & Spivey, 2000; Spivey & Geng, 2001) to remembered or imagined scenes (Johansson et al., 2012; Johansson et al., 2006) and is triggered by linguistic input (Spivey & Dale, 2011).

Jahn and Braatz (2014) applied memory indexing to study sequential diagnostic reasoning. Participants were told to imagine they were physicians diagnosing the chemical with which a worker in a chemical plant was affected during an accident (chemical-accident task, Mehlhorn et al., 2011). Information about symptoms and the chemicals that could cause them were learned during a preceding learning phase. Symptom classes and chemicals (possible diagnoses) were associated to spatial locations. During reasoning trials symptoms were presented auditorily in sequence. Memory indexing showed the activation status of hypotheses in memory over the course of a reasoning trial and indicated how symptoms were interpreted (Jahn & Braatz, 2014). In the study by Jahn and Braatz (2014), in most sequences a single final diagnosis was left after all symptom information had been presented.

The aim of the current study is to show how the study of eye movements can reveal memory processes underlying sequential diagnostic reasoning from the first symptom presentation until a reasoners' response for ambiguous symptom sequences. In order to do so, we applied memory indexing in the chemical accident task (see Jahn & Braatz, 2014). We created 16 item sequences that included a set of critical manipulations: First, to convey the value of process data, we studied symptom sequences that supported two or three contending hypotheses and were ambiguous throughout the symptom sequence such that the same symptom sequence could result in differing diagnoses. Second, we varied the degree of support (one, two or three symptoms supporting one hypothesis) creating symptom sequences with superior support for one hypothesis and sequences with equal support. Third, we manipulated the order of symptom presentation to vary when a hypothesis change becomes likely and to reveal coherence maximizing symptom processing that changes diagnosis proportions for the same symptoms presented in a different order. Fourth, to explore whether participants put more weight on diagnosticity or on diversity based on their implicit assumptions about the scenario, we tested symptom sequences that pitted diagnosticity against diversity.

We assessed diagnostic responses and confidence ratings to test effects of symptom order and diversity. We expect that a hypothesis that receives the most support throughout the symptom sequence is selected over a hypothesis that received less support. Given results on primacy effects, earlier presented symptoms should have a stronger impact on the final diagnosis than later symptoms because of diagnosis momentum. Order effects should be particularly perspicuous for equally supported hypotheses. Furthermore, hypotheses that are supported by symptoms from two symptom classes may be more likely chosen than hypotheses supported by symptoms from one class (diversity effect).

Eye movements are recorded to reveal symptom processing throughout the reasoning process. Gaze data after the first symptom should reflect which hypotheses this symptom supports. Eye movements during subsequent symptom presentations (second till fourth symptom) should reveal diagnosis momentum resulting from symptom processing biased towards a coherent symptom interpretation as well as when in the sequence of symptom presentations a hypothesis change takes place. When giving the response, gaze behaviour should reveal which hypothesis was chosen at the end of the reasoning trial (gaze cascade effect, Shimojo, Simion, Shimojo, & Scheier, 2003).

5.3 Method

The study consisted of a learning phase and a subsequent reasoning phase similar to Jahn and Braatz (2014). During the learning phase, participants acquired the knowledge needed for the reasoning phase. The reasoning task was to determine the most likely cause of a patient's symptoms. The patients were workers in a chemical plant that produces four chemicals and each worker was affected by exactly one of those chemicals.

In the learning phase, participants first learned how symptoms are assigned to symptom classes and second how symptom classes relate to chemicals. Associations between symptom classes and chemicals were established by presenting symptom classes in rectangular frames in four spatial areas that each represented one chemical (Figure 5.1). During reasoning, symptoms were presented auditorily while participants only saw the emptied rectangular frames. Eye movements were recorded throughout the reasoning phase. The diagnostic decision, response times, and confidence ratings were collected at the end of the reasoning trial.

5.3.1 Participants

Of 34 participants, for whom calibration succeeded to an accuracy of at least 2° of visual angle, we had to exclude two participants because the eye tracker lost participants' gaze through the course of the experiment. The final 32 participants were all students from

Technische Universität Chemnitz (21 female, 11 male) with a mean age of 22.4 years (ranging from 19-39 years). All had normal or corrected to normal vision.

5.3.2 Apparatus

Participants were seated at a distance of 63 cm in front of a 22'' computer screen (1680 x 1050 pixels). Stimuli were presented via E-Prime 2.0. Auditory recordings were presented through headphones and responses were given on a standard keyboard. An SMI RED remote eye tracker sampled data of the right eye at 120 Hz. Gaze data were recorded with iView X 2.5 following 5-point calibration and analyzed with BeGaze 2.3. Fixation detection used a dispersion threshold of 80 pixels and a duration threshold of 100 ms.

5.3.3 Material

The four chemicals were assigned to screen quadrants (see Figure 5.1). Each quadrant enclosed three rectangular frames, which contained the three symptom classes that the respective chemical could cause. For example, the chemical at the top left caused symptoms from the symptom classes circulation, pain, and skin. One symptom class was unique (pain for the top left chemical) and two symptom classes were shared with other chemicals. Table 5.1 lists all eight symptom classes and symptoms. Original materials were in German.

Table 5.1 Symptom classes and symptoms (originally in German)

Symptom class	Symptom	Symptom
Eyes (Augen)	Eyelid swelling (Lidschwellung)	Lacrimation (Tränenfluss)
Respiration (Atemwege)	Difficult breathing (Erstickungsgefühl)	Cough (Husten)
Neurological (Nervensystem)	Speech disorder (Sprachstörung)	Paralysis (Lähmung)
Circulation (Kreislauf)	Sweating (Schwitzen)	Swoon (Ohnmacht)
Pain (Schmerzen)	Twinge (Stechen)	Sting (Brennen)
Skin (Haut)	Rash (Ausschlag)	Acid burn (Verätzung)
Digestion (Verdauung)	Vomiting (Erbrechen)	Diarrhea (Durchfall)
Psychoactive (Psychoaktiv)	Aggressivity (Aggressivität)	Anxiety (Angstzustände)

Frames containing symptom classes were arranged in a circle. The distance between the center of the screen and the center of each rectangle was 12.2° of visual angle. The four symptom classes that were uniquely caused by one chemical were presented in the middle of a quadrant (e.g., symptom class pain in the middle of the top left quadrant is located between the symptom classes circulation and skin). The symptom classes that were caused by two chemicals occurred in two quadrants and were presented in two neighboring frames on the circle (e.g., circulation is located top right and top left). Symptoms from symptom classes that were associated with one chemical are denoted with a single small letter (a, b, c, or d). Symptoms from symptom classes that were associated with two chemicals are denoted with two small letters (e.g., symptom ab can be caused by chemical A and chemical B).

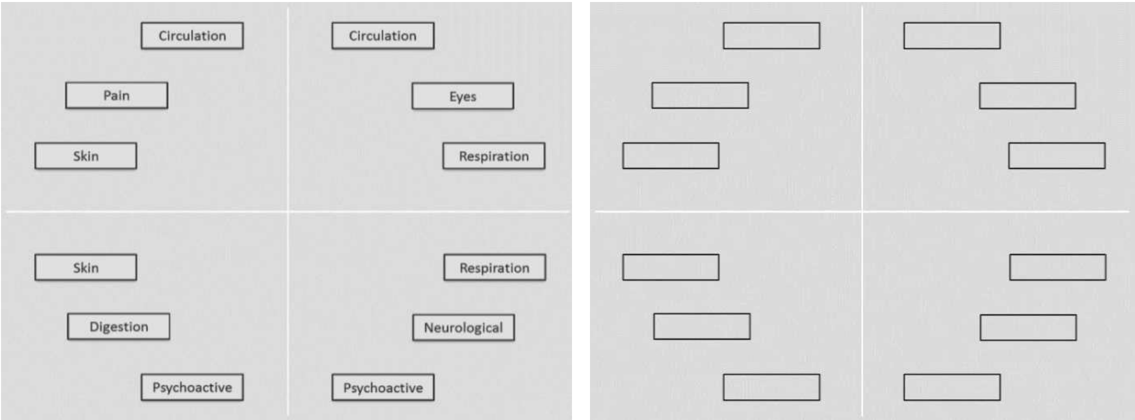

Figure 5.1 Left: Spatial arrangement of the four chemicals and the symptom classes that each chemical could cause as it was presented during learning. **Right:** Emptied spatial arrangement shown during the reasoning phase.

A single trial in the reasoning phase consisted of four symptoms that were presented auditorily, for example, sting, rash, eyelid swelling, and lacrimation. In this example, sting (belonging to the pain class) was associated with the top left chemical, rash (skin) was associated with the top left and the bottom left chemicals, and eyelid swelling (eyes) and lacrimation (eyes) were associated with the top right chemical. We refer to the chemical that we assumed to have an advantage in participants' diagnostic reasoning as the A-chemical. The advantage could be that it was supported by more symptoms than alternative chemicals, that it was equally supported but it had the advantage of being supported by the first symptom or that it was supported by an equal number of symptoms but by symptoms from different classes (diversity). We refer to the competing alternative chemical as the B-chemical, and to further competitors as C- and D-chemicals. In the example, the top left chemical is the A-chemical supported by sting (pain) and rash (skin), the top right chemical is the B-chemical supported by eyelid swelling (eyes) and lacrimation (eyes), the bottom left chemical is the C-chemical supported only by rash (skin), and thus, the sequence sting, rash, eyelid swelling, and lacrimation is an example of an a-ac-b-b sequence. In this sequence, A is supported by a diverse symptom combination; B is supported by a more diagnostic but non-diverse symptom combination.

Across 16 symptom sequences, we varied the degree of support for each chemical (superior support, equal support), the number of supported chemicals, the diversity of support, and the symptom order. The selected sequences by far do not exhaust all possibilities but test our research questions and highlight the value of memory indexing for tracing how diagnoses develop for ambiguous sequences. All tested symptom sequences are presented in the x-axis labels of Figure 5.2. For each symptom sequence, each of the four chemicals once appeared in the A-role. This was possible because the chemicals' symptom class patterns were symmetrical. We constructed all possible assignments of symptoms to symptom sequences with the restriction that no single symptom occurred twice in the same symptom sequence.

Each sequence was tested four times per participant with each chemical in the A-role resulting in 64 (16 sequences * 4 chemicals) trials per participant. The B- and C-roles could be interchanged. For example, if A was located top left, B could be located top right or bottom left. We varied the B and C-roles for each sequence between participants.

5.3.4 Procedure

Learning symptoms and symptom classes. Participants first studied eight symptom classes and their symptoms presented in a similar layout as in Table 5.1 until they felt ready to be tested. Subsequently, they worked through learning trials. In each learning trial, a symptom was presented visually together with a list of symptom classes numbered from one to eight. Participants had to respond with the number denoting the correct symptom class and received visual and auditory feedback. Auditory feedback consisted of a single tone indicating a correct or wrong response. Visual feedback after a wrong response contained the correct answer. The 16 symptoms were presented in random order and in each trial the list of symptom classes to choose from was reordered randomly. The first learning phase continued until all symptoms were once answered without errors. Learning symptoms and symptom classes lasted 11 min on average (*SD* = 10 min).

Learning chemicals and their symptom classes. Next, participants learned about the four chemicals. Participants were presented with the spatial layout as shown left in Figure 5.1 and studied the layout until they felt ready to be tested. During subsequent test trials, participants only saw the emptied spatial frames as shown right in Figure 5.1 and a symptom was presented auditorily. Participants responded by indicating which chemical could have caused the presented symptom by pressing one of the number keys 1, 2, 4, and 5 on the number block of the keyboard. The keys matched the spatial positions of the chemicals (e.g., number 4 indicated the chemical at the top left). Feedback was provided auditorily by a tone signaling a correct or a wrong response. After a wrong response, all symptom classes reappeared in the rectangular frames for two seconds. If a symptom could be caused by two chemicals, after receiving feedback about the first response, participants were prompted to indicate a second chemical and received feedback in exactly the same way as for the first response. Symptoms were presented in random order. There were 24 combinations of symptoms and chemicals. Learning lasted until participants assigned 95 % of all symptoms (23 out of 24 items) correctly. Learning which symptom classes could be caused by which chemicals lasted 10 min on average (*SD* = 9 min).

Reasoning phase. Each reasoning trial was started self-paced by hitting the space bar. The next slide showed the emptied rectangular frames (Figure 5.1, right) and participants were auditorily presented with a sequence of four symptoms. Each symptom presentation lasted 1000 ms followed by a delay of 2000 ms. After the fourth symptom had been presented, participants indicated their diagnosis using the same keys as during learning. Response time was not restricted. Then, the screen containing the emptied spatial frames was replaced by the instruction “Please, indicate how sure you are about your diagnosis” from 1 “very unsure” to 7 “very sure”. Participants rated their confidence with a number on the keyboard and were prompted to start the next trial.

After solving three practice trials at the beginning of the reasoning phase, the eye tracker was calibrated. Subsequently, participants worked through 64 reasoning trials. The reasoning phase was divided in four blocks. Each block consisted of 16 trials, in which all 16 symptom sequences were tested once. The assignment of chemicals to sequences was balanced across blocks and the order of blocks was balanced across participants. For each trial, the assignment of symptoms was drawn randomly from four, six or eight possible assignments for this combination of sequence and chemical. After each block, participants were informed about how many blocks they had finished. Solving the 64 reasoning trials lasted 21 min on average (SD = 3 min).

5.4 Results

We report response proportions for all 16 symptom sequences and mean fixation proportions for a subset of five sequences, in which the first symptom establishes a single leading hypothesis. Gaze data of another three sequences, response time data, and confidence ratings for all 16 sequences are provided as supplemental material.

5.4.1 Diagnostic Response

Diagnostic responses were recorded after the sequence of four symptoms had been presented (end of sequence response mode). Participants chose one of the four chemicals as the most likely cause of the presented symptoms. Figure 5.2.1 shows the proportions of A- and B-responses for ten sequences with two contending hypotheses. Figure 5.2.2 shows response proportions for six sequences with three contending hypotheses.

Participants almost always chose one of the two or three contending hypotheses. Only in 37 trials (1.8 % of all trials) participants chose a chemical that was not supported by the symptom sequence. In 38 trials (1.9 % of all trials) they chose the diagnosis that was only weakly supported by a single symptom that also pointed to a better supported chemical (e.g., C-response after a-ac-b-b). These cases were excluded from further analyses.

If A was the only hypothesis supported by three symptoms (sequences 1 to 3 in Figure 5.2.1 and sequences 1 to 5 in Figure 5.2.2), the A-response proportion was the highest. Thus, people chose the hypothesis that received the most support. For the sixth sequence in Figure 5.2.1 (ab-a-b-ab), the B-response proportion was higher than the A-response proportion. This reflects a strong order effect because sequences 4 to 6 in Figure 5.2.1 provide equal support

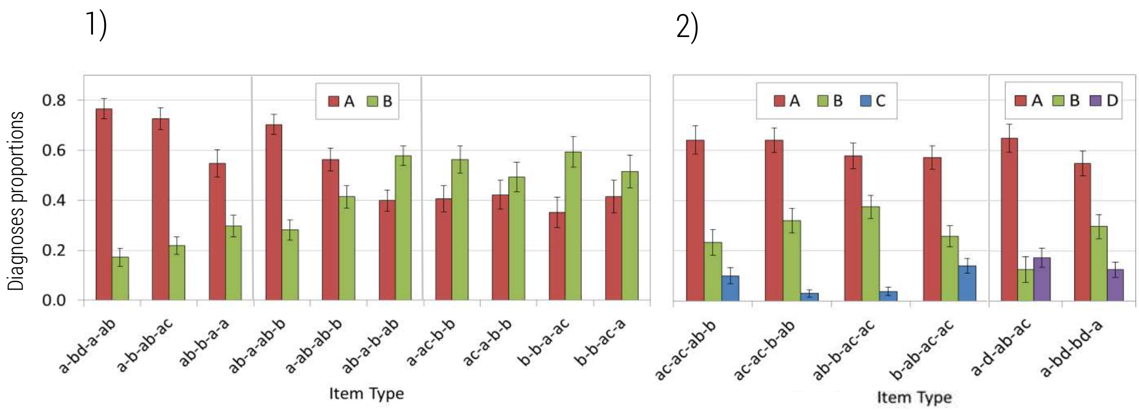

Figure 5.2 1) Mean proportions of A- and B-diagnoses for each symptom sequence with two contending hypotheses. The first three sequences (from left to right) contain superior support for the A-diagnosis. The sequences four to six contain equal support for A and B and consist of the same set of symptoms (symptom order is varied), likewise the remaining four sequences that pit diagnosticity against diversity consist of the same set of symptoms. **2)** Mean proportions of A- and B-diagnoses for each symptom sequence with A-, B- and C- or D-diagnoses for symptom sequences with three contending hypotheses. The first four sequences consist of the same set of symptoms and contain three symptoms supporting the A-diagnosis, all of which support another diagnosis as well (ab and ac). The two sequences on the right included inconsistent symptoms supporting the D-diagnosis (d or twice bd). Error bars show the standard error of the mean.

for A and B and differ only in symptom order. This order effect was confirmed by a significant linear downward trend of A-response proportions across these three sequences, $F(2, 62) = 15.9$, $p < .001$, $\eta_p^2 = .34$.

If two hypotheses were supported by two symptoms each (e.g., A and B in sequences 7 to 10 in Figure 5.2.1) and if three hypotheses were supported by two symptoms each (rightmost sequence in Figure 5.2.2), participants chose more often the hypothesis supported by two maximally diagnostic symptoms from the same symptom class than a competing hypothesis supported by diverse symptoms that (in part or both) were associated with two chemicals: In all four symptom sequences consisting of the symptoms ac, a, b, and b (7 to 10 in Figure 5.2.1), there was a tendency for participants to choose B over A. In the sequence a-bd-bd-a (rightmost in Figure 5.2.2) participants chose A more often than B or D. Thus, diagnosticity was more often evaluated as stronger than diversity. In order to trace the differences in symptom processing resulting in one or the other diagnosis for the same symptom sequence, we analyzed fixation proportions separately for the given responses.

5.4.2 Fixation Proportions

For each trial, we computed the proportion of trial duration for which no gaze data had been recorded. Trials were discarded if more than 40 % of gaze data were missing (4.9 % of all trials) due to blinks, eyes closed or looking off the screen. We analyzed fixation proportions on two levels. First, we report results on fixation proportions on former chemical locations.

Second, for more fine-grained analyses and to reveal symptom interpretation and rehearsal, we report fixation proportions on former locations of symptom classes.

Fixation proportions on former chemical locations. Four areas of interest (AOIs) were defined corresponding to the four spatial areas representing the four chemicals. The AOIs were denoted A, B, C, and D according to the four chemical roles. The center of the screen was not included in the analyses (a circular area around the center of the screen with a diameter of 5.1° of visual angle). Each trial was divided in five time intervals defined by the onsets of each of the four symptom presentations and the response interval. For each of the five intervals and each AOI, we computed the proportion of total fixation time in the four AOIs (screen quadrants excluding the center circle sector) separately for each symptom sequence and each participant and separated by diagnostic response.

Figure 5.3 shows plots of mean fixation proportions across the five time intervals for five symptom sequences starting with an a- or a b-symptom. There are separate plots for trials with A-, B- and D-responses (left, middle, and right column, respectively). The symptom sequences in Figure 5.3 are ordered from top to bottom according to the number of consecutive symptoms that supported the A-hypothesis from the beginning of the sequence onward. The sequence in the first row started with three symptoms supporting A (a-ab-ab-b). The sequence in the second row started with two symptoms supporting A (a-ac-b-b). The sequences in the third and fourth row started with a single a-symptom (a-bd-bd-a and a-bd-a-ab). And finally, the sequence in the fifth row started with a b-symptom (b-ab-ac-ac). Although, the proportions of B-responses for these sequences varied (Figure 5.2), the ordering in Figure 5.3 conveys in the B-response column that participants switched their leading hypothesis the earlier from A to B the earlier the series of A-supporting symptoms ended (hypothesis change). In the following, we focus on gaze data showing the generation of a leading hypothesis and subsequent biased symptom processing either favoring the leading hypothesis or resulting in a hypothesis change.

First symptom interval. In the first symptom interval, fixation proportions should reflect how much the first symptom supported each individual hypothesis (momentary probability matching). As expected, this was the case for all symptom sequences displayed in Figure 5.3. The first four symptom sequences (first till fourth row of Figure 5.3) began with an a-symptom. Accordingly, the A-quadrant in the first interval was fixated longer than the other three spatial areas B, C and D. Vice versa in the symptom sequence starting with a b-symptom at the bottom of Figure 5.3, B is fixated longer than A in trials finally responded to with B.

Second till fourth symptom interval. Fixation proportions during subsequent symptom presentations reflected the subjective probabilities of the respective chemical as cause of a symptom. The memory indexing gaze data differed between trials of the same symptom sequence with differing final responses and reflected both the support provided by symptoms and biased symptom processing (diagnosis momentum).

Fixation proportions reflected differences in support of alternative hypotheses in the symptom sequences: In trials with A-responses, the A-fixation proportion dropped the earlier symptoms supported an alternative hypothesis. Vice versa in trials with B-responses, fixation proportions for B increased the earlier a B-supporting symptom was presented. In the sequence a-bd-bd-a, a third hypothesis D was as supported as B. In trials with D-responses, the most fixated quadrant shifted from A to D (Figure 5.3, third row).

The observed change in fixation proportions induced by a symptom differed depending on the final response (diagnosis momentum): For example, in the sequence a-ab-ab-b (Figure 5.3, top row) with a final A-response, B received almost no fixations in the second and third interval in comparison to A, which was fixated more than 60 % of the time in each interval. In contrast, with a final B-response, the B-proportion increased after the ab-symptoms. Similarly, in the sequence a-bd-a-ab (Figure 5.3, fourth row) with a final A-response, the inconsistent bd-symptom was ignored as can be seen in the low fixation proportions for the B- and D-quadrants. However, with a final B-response, the bd-symptom led to a strong increase in fixation proportions for the B-quadrant.

With regard to the sequences that pitted symptom diversity against symptom diagnosticity, it is of interest whether the second b-symptom in the sequence a-ac-b-b (Figure 5.3, second row) was taken as further support for B and thus increased the B-proportion. Indeed, the second b-symptom led to an increase in fixation proportions towards the B-chemical. This increase was even more pronounced when responding with B in comparison to A. Similarly, in other symptom sequences the repetition of the same symptom class induced further changes in fixation proportions.

Response interval. Evidence accumulation continued until the response interval. When responding, fixation proportions were always highest for the chosen alternative. This was the case for all item types and responses plotted in Figure 5.3. Such increasing fixation proportions in favor of the chosen alternative have been described as gaze cascade effect.

Fixation proportions on former locations of symptom classes. We defined twelve small AOIs around the twelve emptied rectangles that had contained information about symptom classes during learning. The small AOIs exceeded the border of a rectangle by half its height in each direction. AOIs were labeled according to the respective chemical’s role in a trial. The middle rectangle within each quadrant always contained a symptom class that was unique for this chemical and was therefore labeled a, b, c or d. Symptom classes in the remaining rectangles were associated with two chemicals and were therefore labeled with two letters: the first letter indicated the quadrant in which the rectangle was located and the second letter indicated the adjacent quadrant that contained this symptom class as well. For example, there were two rectangles that contained the symptom class ab (e.g., skin). The AOI for the rectangle that was located in the A-quadrant was called ab and the AOI for the rectangle that was located in the B-quadrant was called ba.

Similar to the analyses based on quadrant-AOIs, we computed the proportion of time that each small AOI was gazed at within one of the five time intervals for each trial and aggregated fixation proportions per symptom sequence and participant separated by diagnostic response. Figure 5.4 shows mean small-AOI fixation proportions for the same five symptom sequences that are shown in Figure 5.3. Figure 5.4 only shows fixation proportions for small AOIs associated with the two or three competing hypotheses. Fixation proportions for other small AOIs were negligible (cf. Figure 5.3).

First interval. In the first time interval, fixation proportions were increased for the small AOI that had contained the symptom class of the presented symptom. If the first symptom was a, the a-AOI was fixated longer than any other small AOI (Figure 5.4, first till fourth row). Vice versa, if the first symptom was b, the b-AOI was fixated the longest (Figure 5.4, bottom row).

Second till fourth symptom interval. Fixation proportions in subsequent time intervals reflected subjective interpretations of symptoms and symptom rehearsal. Similar to the quadrant-AOIs, they showed biased symptom processing in favor of the leading hypothesis. When an ab-symptom was presented, both the ab- and ba-AOIs were gazed at. However, if A was the leading hypothesis, ab was fixated longer than ba (first, fourth and fifth row of Figure 5.4). Thus, symptoms were interpreted in the direction of the leading hypothesis (diagnosis momentum). Biased symptom processing was generally obvious when comparing fixation proportions for the same symptom sequence between trials with differing responses. In trials with A-responses, small AOIs in the B-quadrant were almost not fixated and in trials with B-responses, small AOIs in the A-quadrant received only few fixations in symptom intervals following B-supporting symptoms (Figure 5.4).

Moreover, analyses of small AOIs revealed that previously heard symptoms were rehearsed (symptom rehearsal). For example, when an a-symptom was presented in the first symptom interval, fixation proportions towards the a-AOI were increased in subsequent intervals (Figure 5.4). The same can be seen for ab- and bd-symptoms.

Response interval. When giving the response, fixation proportions were increased for those small AOIs that had contained the respective symptom categories in the quadrant of the chosen hypothesis (gaze cascade effect).

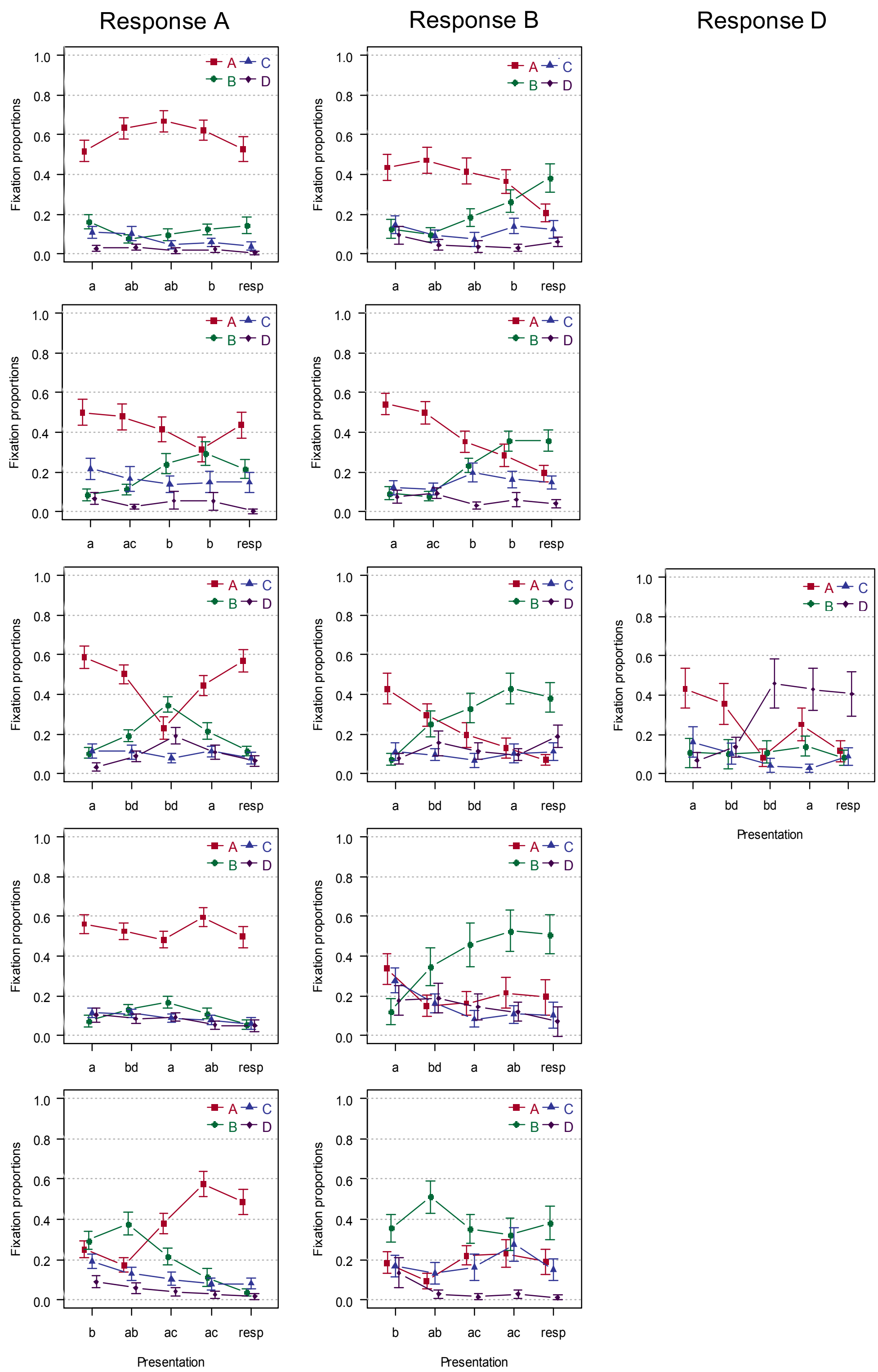

Figure 5.3 Mean proportions of fixation times in each interval that fell upon the A-, B-, C-, or D-quadrants for four ambiguous symptom sequences with two contending hypotheses (A-responses left column, B-responses middle column) and one ambiguous sequence with three contending hypotheses (additionally D-responses right column). Error bars represent one standard error.

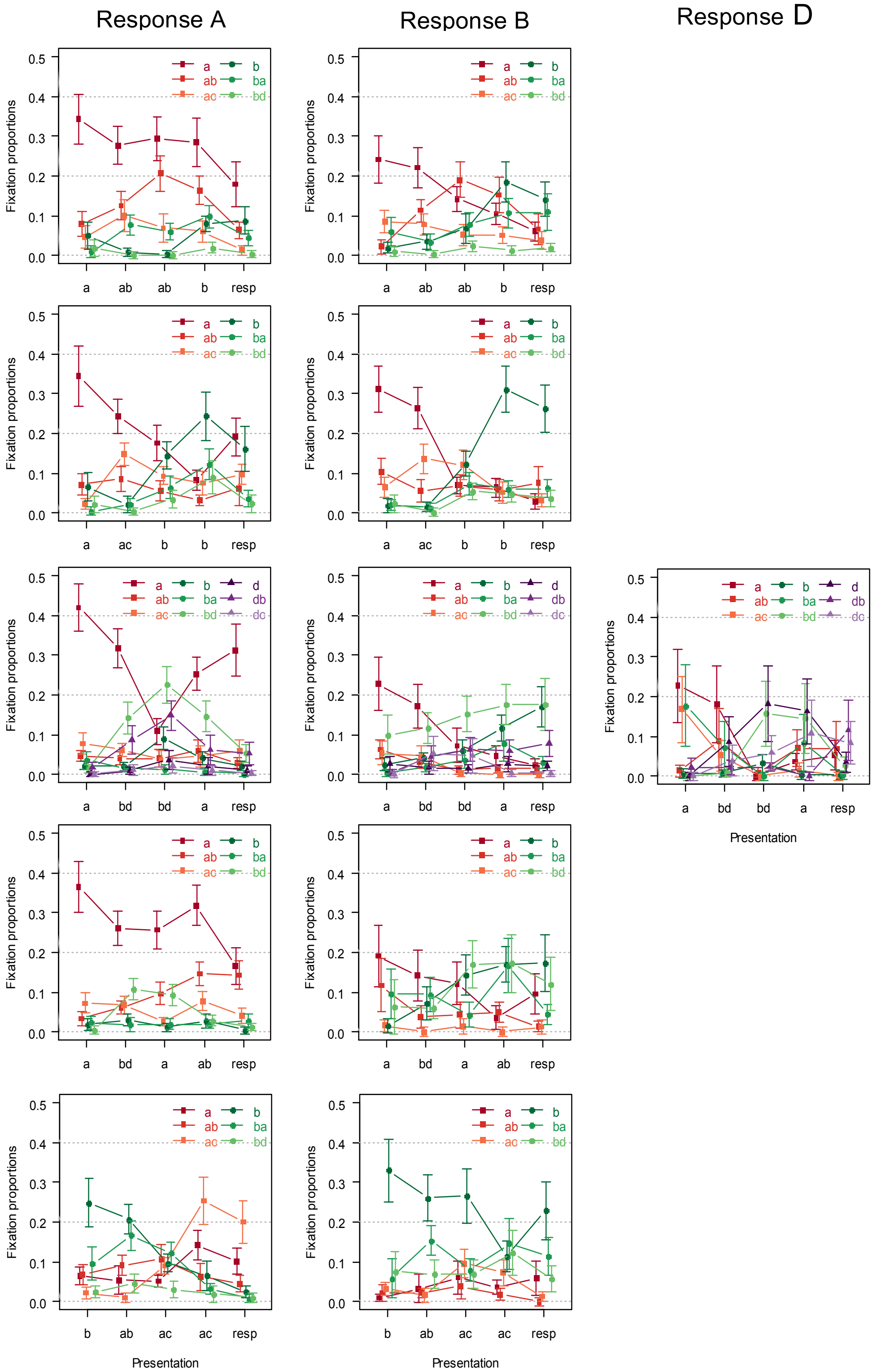

Figure 5.4 Mean proportions of fixation times in each time interval that fell upon the areas of interest around the rectangles containing symptom classes during learning. Four ambiguous symptom sequences with two contending hypotheses are shown that are separated in A-responses (left column) and B-responses (middle column). Additionally, one ambiguous sequence with three contending hypotheses is shown and fixation proportions before D-responses for this sequence are shown in the right column. Only those fixation proportions are plotted that correspond with the competing hypotheses (A and B or A, B and D). Error bars represent one standard error.

5.5 Discussion

In everyday life, humans have to cope with ambiguous, uncertain situations. This is particularly clear when people have to find an explanation for a set of inconclusive observations. How do people cope with ambiguity in such challenging instances of diagnostic reasoning? Outcome data suggest that people strive for a coherent interpretation of observations. This claim results in a number of process assumptions: Interpreting new symptom information should be biased towards the leading hypothesis and information should be rehearsed and accumulated resulting in an hypothesis change when an alternative hypothesis receives more support than the previously favored competing explanation (Busemeyer & Townsend, 1993; Lange et al., 2012; Trueblood & Busemeyer, 2011; Weber et al., 1993). However, observing these presumed processes directly was not possible before. We tested these process assumptions using memory indexing, a new method that is based on observing eye movements while participants solve memory-based reasoning tasks (Jahn & Braatz, 2014; Renkewitz & Jahn, 2012). We provided evidence that eye movements indeed reflect the tendency to maximize coherence in diagnostic reasoning. We showed these effects with symptom sequences that were highly ambiguous and tested effects of presentation order and symptom diversity.

At the beginning of a reasoning trial, gaze behaviour reflected the momentary probability of hypotheses given the presented symptom information. However, eye movements did not just reflect (automatic) retrieval processes initiated by hearing an auditorily presented cue. Instead eye movements reflected the dynamic updating of memory for hypotheses and symptoms. During subsequent symptom presentations, eye movements were predominantly directed to locations of symptom interpretations consistent with the leading hypothesis and not to all locations that were associated with the presented symptom. This finding is in line with previous research demonstrating symptom integration with varying symptom strengths (Jahn & Braatz, 2014).

The use of ambiguous symptom sequences resulted in varying responses to the same sequence of symptoms and thus, afforded to analyze gaze behaviour by response. This analysis by response clearly showed that the final response developed in a process of biased symptom processing and maximizing coherence. In maximally ambiguous items (e.g., a-ab-ab-b), the bias towards the initially leading hypothesis was reflected in response proportions. Gaze behaviour revealed how this advantage of the leading A-hypothesis developed but also, how the hypothesis change developed in the less frequent trials, in which the competing B-diagnosis was chosen. By directly tracing biased symptom processing unobtrusively, memory indexing provides strong evidence for theories postulating coherence maximizing and information distortion (Kostopoulou et al., 2012; Russo et al., 1996; Wang et al., 2006).

A subset of the symptom sequences pitted diagnosticity against diversity of symptoms (b and b against a and ac, and a and a against bd and bd). In the present study, response proportions indicated that participants went with diagnosticity slightly more often and gaze behaviour showed that a second symptom from the same symptom class (b after b) was taken as additional evidence. This response tendency cannot be compared to a normative standard because critical information for computing a normative decision (causal structure, causal strengths, base rates, alternative causation, and presence of unstated symptoms) was implicit and unspecified. It is quite likely that participants would rather choose the diversely supported hypothesis if critical information favoring diversity was provided (Rebitschek, Krems, & Jahn, 2014).

Bridging two lines of research, eye movements to emptied spatial locations on the one hand and diagnostic reasoning on the other hand, revealed the processing of ambiguous symptom information and allowed deep insights into the underlying cognitive processes. As the present memory indexing results underscore, tracing cognitive processes in highly complex tasks is crucial for a better understanding of human cognition and informs process models of reasoning and decision-making. In particular, memory indexing results on diagnostic reasoning may help in revising existing theories about diagnostic reasoning and in developing efficient support systems to guide diagnosticians and to prevent misdiagnoses and overconfidence.

5.6 Supplemental Material

5.6.1 Mean Response Times

Response times were computed after trimming outliers 3 *SD* above the individual session means (2.6 % of the data). One participant produced more than twice the average response time and was not included in the analysis of mean response times. Response times were measured from the onset of the response. Mean response times for a and b responses were aggregated per participant and item type (Figure A.5.1).

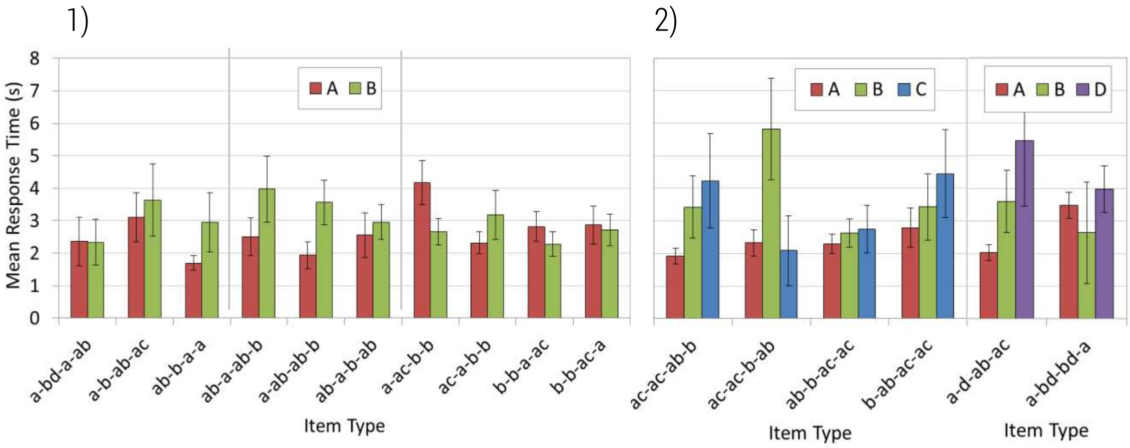

Figure A.5.1 1) Mean response times of A- and B-diagnoses for each symptom sequence with two contending hypotheses. 2) Mean response times of A- and B-diagnoses for each symptom sequence with A-, B- and C- or D-diagnoses for symptom sequences with three contending hypotheses. Error bars show one standard error.

5.6.2 Mean Confidence Ratings

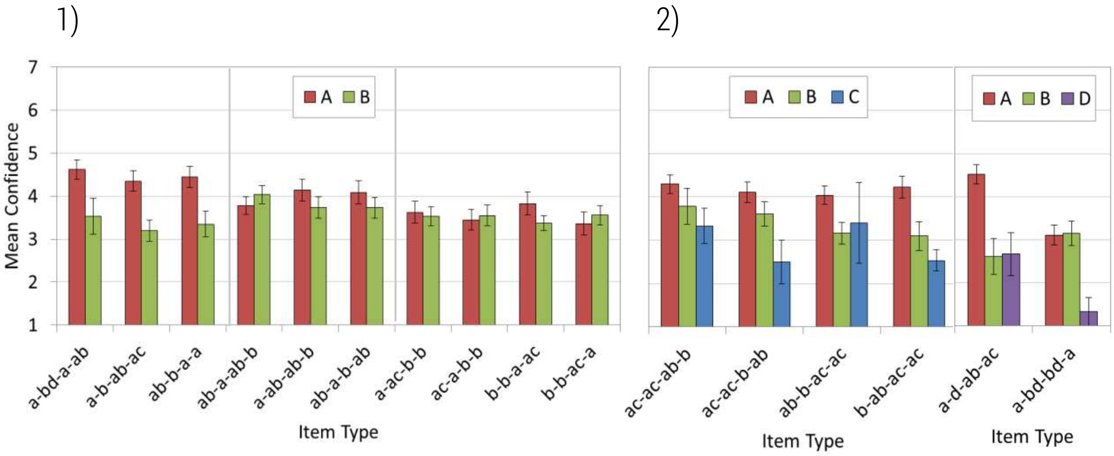

Figure A.5.2 1) Mean confidence ratings of A- and B-diagnoses for each symptom sequence with two contending hypotheses. 2) Mean confidence ratings of A- and B-diagnoses for each symptom sequence with A-, B- and C- or D-diagnoses for symptom sequences with three contending hypotheses. Error bars show one standard error.

5.6.3 Fixation Proportions

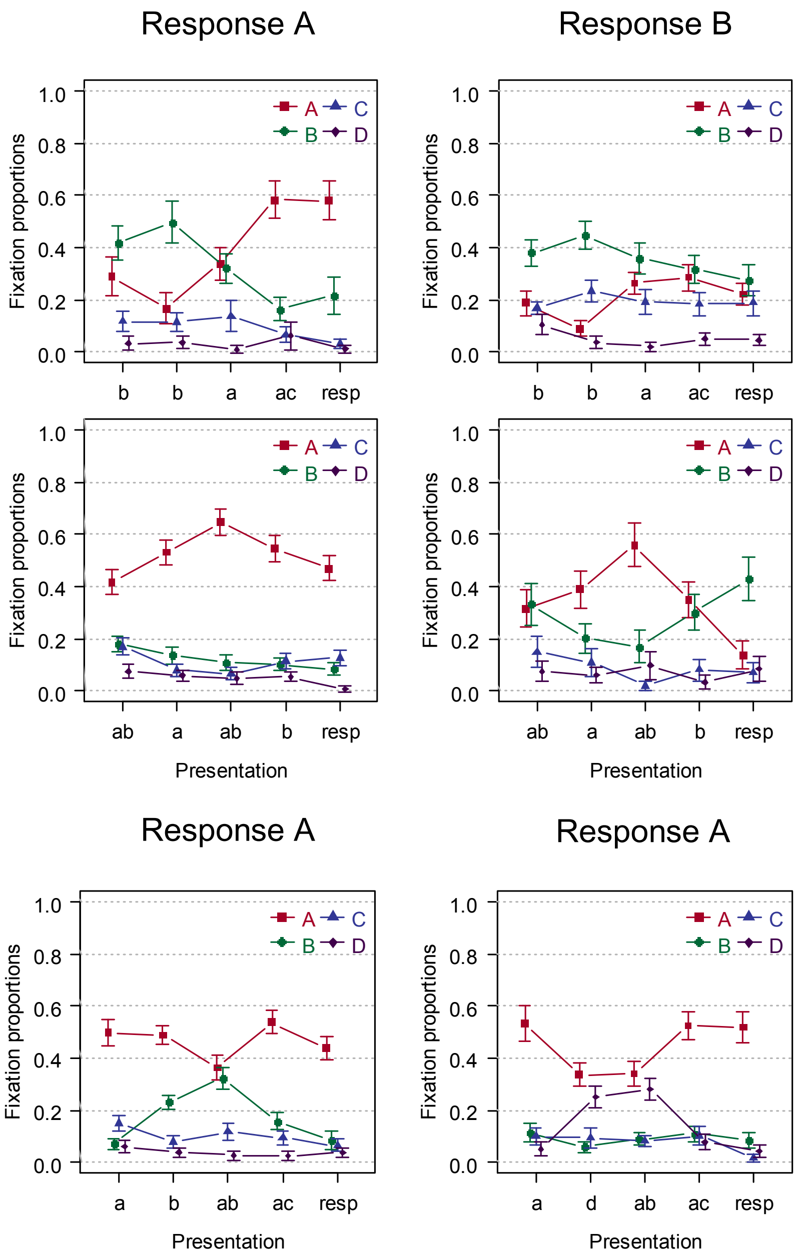

Figure A.5.3 Mean proportions of fixation times in each interval that fell upon the a, b, c, or d quadrants for two ambiguous symptom sequences with two contending hypotheses and A- and B-responses and two ambiguous symptom sequences that only differ in the second symptom (b versus d) and A-responses. Error bars represent one standard error.

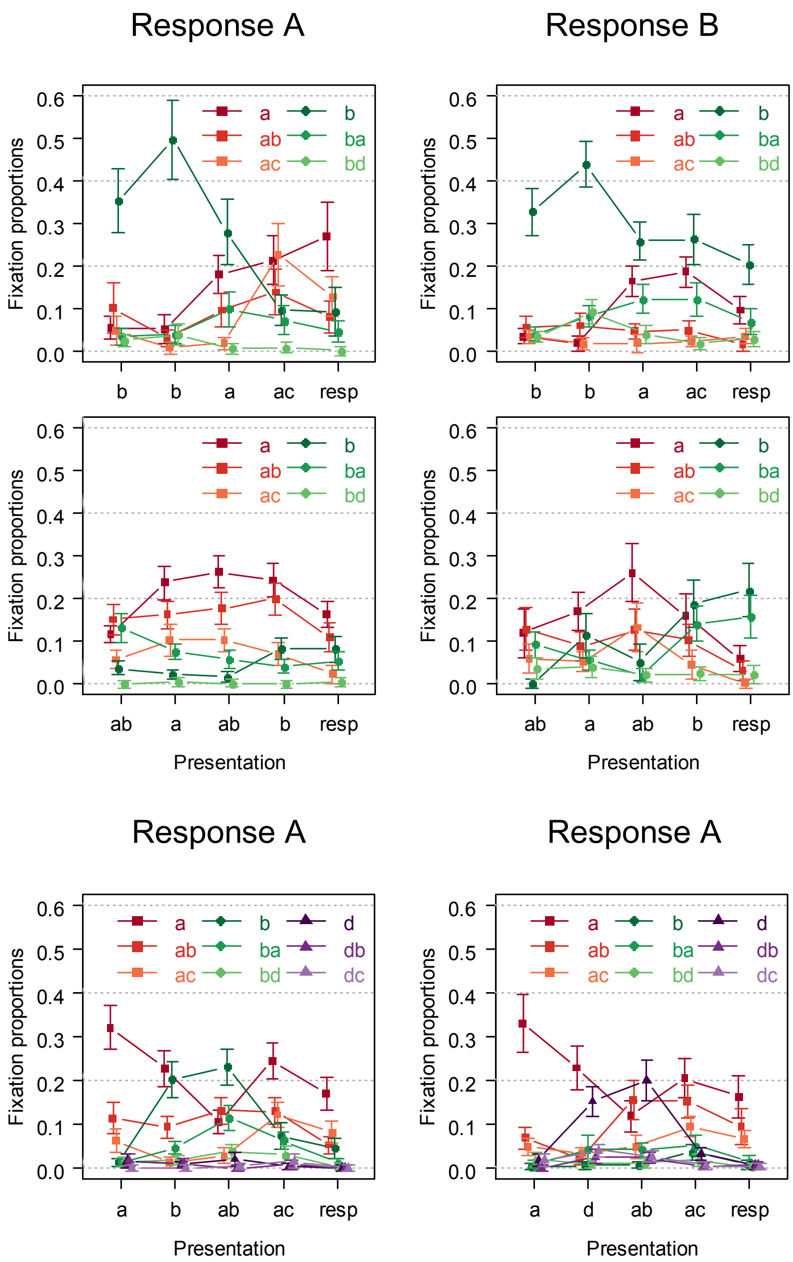

Figure A.5.4 Mean proportions of fixation times in each time interval that fell upon the areas of interest around the rectangles containing information on symptom classes during learning. Two ambiguous symptom sequences with two contending hypotheses are shown that are separated in A-responses (left columns) and B-responses (middle column). Additionally, two ambiguous symptom sequences that only differ in the second symptom (b versus d) and A-responses are plotted at the bottom. Only those fixation proportions are plotted that correspond with the competing hypothesis (A vs. B or A, B vs. D). Error bars represent one standard error.

6 Summary and Conclusion

Building on the research conducted on dynamic spatial indexing of multimodal events, this thesis focused on eye movements, both as a cause and as a consequence of memory retrieval. The main findings can be summarized as follows:

Research objective 1: Eye movements during the retrieval of verbal information from memory are functionally related to retrieval performance

When retrieving information that was auditorily presented during encoding, simultaneous to the presentation of an abstract symbol at a spatial location, people proportionally fixated on average 36 % of the time in the spatial area associated with the probed content. This is much higher than the chance level of 25 % (given four spatial areas) would predict. This behaviour is more pronounced when giving a correct response in comparison to an incorrect response. Whereas this relationship is only correlational, this study was also able to demonstrate that eye movements are functional by manipulating eye movement behaviour as an independent variable and measuring the effect of this manipulation on response accuracy and response times. Guiding the eyes away from the associated spatial location with the help of a salient spatial cue reduces retrieval performance by on average 10 %. Eye movements are thus functionally related to memory, even in terms of the retrieval of verbal information (Chapter 2).

Research objective 2: Eye movements are not automatically launched to spatial locations. On the contrary, eye movements reflect the dynamic updating of information held in memory

When presenting participants with the same information several times and probing this information in exactly the same manner, the looking-at-nothing behaviour is reduced (Chapter 3). Additionally, research findings presented in Chapters 4 and 5 do also confirm to this conclusion: The execution of eye movements to associated spatial location depends on the retrieval strategy (Chapter 4). Whereas using the similarity of a new object to stored instances in memory leads the gaze back to spatial locations associated with the retrieved exemplars, using an abstract rule does not. Furthermore, gaze behaviour reflects the dynamic updating in memory of hypotheses and symptoms (Chapter 5). Gaze behaviour was therefore only directed to symptoms associated with explanations that belonged to a set of contending hypotheses and not to all locations that were associated with a certain symptom.

Research objective 3: Eye movements can be used as a direct behavioural correlate of memory processes involved in rule-versus similarity-based decision-making

Eye movements have been employed as a tool to study memory-based binary decision-making and diagnostic reasoning (memory indexing). Chapter 4 describes how memory indexing can also be a useful tool to explore rule- and similarity-based decision processes. Gaze behaviour was compared between participants that were instructed or who had spontaneously adopted an abstract rule, with participants using similarity to previously learned instances stored in memory. Gaze behaviour revealed that participants using similarity gazed back to associated spatial locations whereas participants using an abstract rule did not show this behaviour. Given the results on dynamic spatial indexing of multimodal events, this suggests that participants using the similarity strategy retrieve information about previously learned exemplars from memory, whereas this is not the case for participants using an abstract rule. Eye movements can in this way reveal differences in memory processes that are caused by different decision strategies.

Research objective 4: Eye movements reveal the development of hypotheses in memory throughout the process of diagnostic reasoning of ambiguous symptom sequences from the first symptom presentation until the response

Evidence has recently been published that demonstrates how memory indexing can be applied to the study of diagnostic reasoning. The experiment reported in Chapter 5 continued this line of research by studying ambiguous symptom sets in which the order of the presented symptoms varied and consisted of equal numbers of maximally diagnostic but non-diverse symptoms supporting one hypothesis, and less diagnostic but more diverse symptoms supporting another hypothesis. Ambiguous symptom sets permit different final diagnoses with this therefore allowing for the analysis of gaze behaviour dependent on the final response. Memory indexing traced how the diagnostic decision developed, and it revealed instances of hypothesis change and biases in symptom processing from the first symptom presentation until the participant's response. Memory indexing thus provided direct online evidence for information distortion and coherence maximization in processing ambiguous information.

6.1 Eye Movements Reflect Memory Dynamics

Different attempts have been made to explain how eye movements relate to memory. On the one hand, researchers assumed that eye movements are merely a byproduct or epiphenomenon of memory activity (e.g., Anderson, Bothell, & Douglass, 2004; Micic, Ehrlichman, & Chen, 2010). This school of thought recognizes eye movements as a consequence of memory retrieval, unable to feedback information into the retrieval process. An alternative perspective assumes that eye movements take an active role in memory processing (e.g., Ballard et al., 1997; Hollingworth, 2005a, 2005b, 2006). They feed visual information into the cognitive system, and are thereby an integral part of the updating process of multimodal memory representations. This updating process was described by Spivey and Dale (2011, p. 554) as follows: “The ongoing processes of cognition ‘spill over’ (before a decision is final) into the oculomotor system, causing it to prepare partially-active movements plans that are consistent with the gradually accumulating perceptual evidence […] This flow of information can be described in a continuous perception-action cycle (Neisser, 1976) and becomes an autocatalytic causal loop, in which cognition emerges.” The results of the experiment described in Chapter 2 of this thesis are in line with Spivey and Dale’s above account. If eye movements are merely an occurrence at the end of a chain of events as a consequence of memory retrieval, a gaze manipulation, as demonstrated in Experiment 2, should not have affected retrieval performance. This study did show however that retrieval accuracy does indeed vary with different gaze cueing conditions.

Alternative explanations for the functionality of eye movements being directed towards blank spaces have been formulated. Importantly these explanations do not exclude each other. On the contrary, they emphasize different aspects of the retrieval process. Firstly, eye movements may act as a “facilitatory cue” (Johansson, 2013, p. 66). Re-enacting processes that were active during encoding (like the recreation of an eye movement towards an associated spatial location) increases memory activity of information stored in the multimodal memory representation (see Chapter 2 for a detailed literature review). Through this re-enacting process, the to-be-retrieved information becomes more available in memory (Platzer et al., 2014). Secondly, research on mental imagery has highlighted that eye movements are part of constructing and maintaining a mental image (Borst & Kosslyn, 2008; Brandt & Stark, 1997; Kosslyn, 1994; Laeng et al., 2014), thereby exploiting both the internal and external memory resources (O’Regan, 1992; Spivey, Richardson, & Fitneva, 2004) to reduce processing demands (Borst & Kosslyn, 2008; Brandt & Stark, 1997; Johansson et al., 2012, 2010; Kosslyn, 1994; Laeng et al., 2014). This is true both for mental images constructed from visuospatial information as well as verbal information.

Following this latter concept, one could assume that eye movements towards blank spaces act as mnemonic strategy. This seems plausible given the frequently reported behaviour of people knowing where something was written and then attempting to retrieve what was written there. However, none of the participants in the here presented experiments reported that they used their gaze to structure the to-be-encoded information. Furthermore, eye movements are assumed to be highly automatic actions (Irwin, 2004; Rayner, 2009; van Gompel et al., 2007; Yantis & Jonides, 1981). Eye movements directed towards blank spaces are therefore an unlikely candidate for usage as a conscious mnemonic strategy.

Although, there have been numerous examples demonstrating eye movements directed towards blank spaces (see Introduction) under a variety of conditions, are there situations were looking-at-nothing is not displayed? In this thesis, this was exemplified in the experiment described in Chapter 3, in which the same set of information was presented twelve times. It was also shown to occur in the first experiment described in Chapter 4, in which participants failed to gaze back to the instruction location during decision-making. A possible explanation for this observation could be that when information is highly activated in memory, people do not gaze back to associated spatial locations. Retrieving highly activated knowledge from memory needs less attentional resources (for an overview see Birnboim, 2003). Furthermore, the knowledge representation could have changed from an episode to a (abstract) semantic representation in which spatial representations did not play a role. For instance, long-term information retrieval is also possible without showing directed eye movements (Micic et al., 2010). Additionally, due to it no longer being necessary to update the knowledge representation given that the perceptual information becomes stable over trials. The network of associated knowledge hence becomes stable and does not afford the execution of a motor response to gather information from the external world (e.g., O'Regan, 1992).

In either case, such a situation should not be intermingled with one in which knowledge is stably represented in long-term memory and needs to be actively processed in order to make a decision (Chapter 4) or find a likely explanation for a set of observations (Chapter. 5): In the first case, looking-at-nothing depends on the retrieval strategy. When a retrieval strategy calls for the retrieval of past instances stored in memory, as is the case during a similarity-based judgment, looking-at-nothing occurs, but it fails to occur when applying an abstract rule (Chapter 4). Importantly, participants applying an abstract rule also knew the cue information by heart. Such strategy dependent looking-at-nothing has been shown for the comparison of non-compensatory to compensatory heuristic decision-making (Renkewitz & Jahn, 2010, 2012). In the experiment described in Chapter 5, the same symptom was associated with two different spatial locations. Each spatial location belonged to a larger spatial area representing different explanations. Participants only gazed at those spatial locations that were associated with explanations currently in the set of contending hypotheses. They did not gaze at spatial locations associated with identical symptoms that were associated with a different explanation (c.f. Jahn & Braatz, 2014). These findings are in line with Hoover & Richardson (2008) who showed that participants only gazed towards an identical looking object, if that object was associated with the to-be retrieved information.

To summarize, eye movements towards blank spaces depend on how information is represented in memory. Furthermore, evidence is accumulating that the eyes are not automatically launched to all associated spatial locations, but instead looking-at-nothing reflects the highly dynamic updating of information held in multimodal memory representations and in long-term memory. However, future research is needed to further clarify when eye movements are launched to blank spaces.

6.2 Eye Tracking to Study Reasoning and Decision-Making

To explain thinking processes, it is essential to describe changes in the underlying memory-based mental representations (see Introduction). This however requires suitable methods. Outcome measures such as response data (e.g., the chosen alternative) can be used to differentiate between normative solutions to a problem (e.g., correct or incorrect conclusions), but, such measures are inappropriate to describe the underlying processes, given that often different processes result in the same outcome. Moreover, outcomes allow for the consideration of only a subset of observable behaviours (e.g., Renkewitz & Jahn, 2010, 2012). In comparison, process tracing permits the testing of hypotheses concerning intervening processes preceding a decision or inference (e.g., what information is retrieved from memory and in which temporal order). Many successful process measures have been developed; namely verbal protocols, thinking aloud, functional imaging, response times (e.g., the probe reaction task, Mehlhorn et al., 2011), and mouselab (Payne et al., 1993) (for an overview see Schulte-Mecklenbeck et al., 2011). Eye movements were also considered a process measure, but only for the investigation of information derived from givens. Renkewitz and Jahn (2010, 2012) and Jahn and Braatz (2014) have shown that eye movements can be used to study memory-based reasoning and decision-making by drawing upon findings on dynamic spatial indexing of multimodal events (the memory indexing method).

The results presented in Chapters 2 to 5 strengthen the assumption that eye movements can be used as a direct behavioural correlate for the retrieval of information from memory by demonstrating the tight interplay of eye movements and memory retrieval (Chapter 2), by showing that eye movements reflect which information is retrieved from memory (Chapter 4) and by clarifying which explanations belong to a set of contending hypotheses (Chapter 5).

The experiments presented in Chapter 4 demonstrate how memory indexing can be applied to the investigation of rule- versus similarity-based decision-making. Whereas the differentiation between an abstract rule and an exemplar retrieval process might evoke memories of long lasting debates about one or two processes (e.g., Hahn & Chater, 1998; Pothos, 2005), the purpose of this study is not to emphasize dichotomies. On the contrary, by exploring underlying cognitive processes, this thesis endeavours to emphasize that it is the same cognitive system operating the same set of mechanisms to solve a task; a cognitive system that can either apply an abstract rule or compare a new observation with instances stored in memory. If this was not the case, this study would not have been successful in using memory indexing, which draws upon the cognitive mechanism of multimodal spatial indexing, to explore this topic.

In Chapter 5, this study showed that memory indexing can reveal the activation status of information held in memory from the first symptom presentation until the participants' response. For each moment a new piece of information is presented, eye movements reflect the relative importance of this information in the light of other information, thus it reflects the integrated likelihood (cf. Jahn & Braatz, 2014) of a hypothesis held in memory, and allows the testing of process assumptions (e.g., evidence accumulation, diagnosis momentum, hypothesis change, see Chapter 5).

In order to reveal memory-processes involved in reasoning and decision-making by applying the memory indexing method, some methodological issues should be taken into account:

(1) Clear hypothesis about expected gaze events. It is of course an over simplification to assume that this study merely expounds the concept "Tell me where you look, and I tell you what you think". This thesis instead aims to demonstrate that thinking is a highly complex process, and that eye movements are influenced by many factors (see Introduction). Precise assumptions are required to gauge which eye movements are expected given a certain thinking process. This point tackles the question of which dependent variable to use (e.g., movement, latency, or numerosity measures; for a comprehensive overview see Holmqvist et al., 2011) and where participants are expected to look (position measures, areas of interest), because: "process tracing is at its best when clearly formulated hypotheses exist that directly relate to process data" (Schulte-Mecklenbeck et al., 2011, p. 737).

(2) Unambiguous assignment of information to locations. In order to draw a conclusion as to what a certain gaze means, it is necessary that each location which can be subject to gaze behaviour is associated with one information unit of interest (e.g., one symptom, one piece of verbal information, one cue value).

(3) Randomizing presentation order to control for gaze biases. As explained in the introduction, gaze behaviour is not only influenced by the top-down mechanism of interest, but is also affected by bottom-up factors. Additionally, people have a tendency to gaze at the center (Tatler, 2007), and in western societies there is the convention to read from left to right (e.g., Liversedge & Findlay, 2000). It is essential to take these natural gaze biases into account (e.g., by experimentally controlling them) when designing experiments.

(4) Control for prior knowledge. To give every information the same chance to be gazed at and thus to be processed, each piece of information should have the same likelihood of being retrieved from memory. Otherwise gaze behaviour will resemble the ease of retrieval and not the cognitive mechanism of interest.
(5) Record enough data. Valid eye tracking data needs to measure the process of interest. Like response times however, the data may be subject to the influence of noisy data due to the unintentional recording of task-irrelevant processes (e.g., participants being distracted due to thinking for example about when the experiment might conclude). In order to gain enough experimental power and gain a good estimate of the behaviour of interest, it is essential to collect enough data points for each cell in the design and test a sufficient number of participants.
(6) Method triangulation. Eye movements as a process tracing tool should not be seen as an alternative to other existing process measures or process models (e.g., computational models of reasoning and decision-making processes – see Chapter 4). Process data derived from eye movements should be used to supplement and support existing mathematical descriptions (see Weber & Johnson, 2009; Jahn & Braatz, 2014). Promising examples are provided by Krajbich, Armel, and Rangel (2010), Krajbich, Lu, Camerer, and Rangel (2012), and Nederhouser and Spivey (2004).

These challenges in successfully studying eye movements as a measurement to explore thinking processes demonstrate that this method is best applicable in a laboratory setting following a classical experimental approach. The alternative of the outside world poses a myriad of challenges given that almost always something is visible and therefore we continuously update our mental representations (e.g., Spivey & Dale, 2011). Consequently, the results obtained by memory indexing lack external validity. For example, a physician making a diagnosis would not have to retrieve all the necessary medical information solely from memory, but would combine test results and verbal reports with knowledge retrieved from memory. Nevertheless, it is important to isolate single cognitive mechanisms and study them in a laboratory setting, as this allows for the testing of precise hypotheses and the drawing of causal inferences; both necessary steps in suggesting explanations. Such findings can then be replicated in the field setting or used as starting point for more applied research questions.

6.3 Future Research and Applications

This final section provides an outlook for future research, and briefly discusses possible applications of the research findings presented within this thesis.

With regard to the mechanisms that cause the looking-at-nothing behaviour, i.e. dynamic spatial indexing of multimodal events, it is of interest to identify if it is the overt movement of the eye per se, or if covert shifts of attention are sufficient to cause differences in retrieval performance as elicited by a gaze instruction (see Chapter 2). Richardson and Spivey (2000) showed that people looked at blank spaces, even when they did not have to move their eyes to spatially index one of the four spatial areas during encoding (Experiment 5). Thomas and Lleras (2009) asked their participants to solve Duncker's radiation problem. While doing so, participants had to either shift their attention (while keeping the eyes at the center of the screen) or move their eyes in an order that corresponded to the solution of the problem. Both groups solved the problem faster than a third group which was instructed to gaze at the center of the screen. These results suggest that attention shift in addition to eye movements appear to guide insight. Anja Prittmann (Prittmann, 2014) tested if in the looking-at-nothing paradigm eye movements are necessary to elicit differences in retrieval performance or if the same result can be obtained by merely shifting attention. Participants were only allowed to either move their eyes or to shift their attention when remembering auditorily presented pieces of information that had been associated to a spatial area during an encoding phase. The results suggested that covertly shifting attention towards the emptied spatial area does indeed lead to a better retrieval performance than covertly shifting attention away from the associated spatial area. Covert shifts of attention therefore were sufficient to cause differences in retrieval performance. Attention seems to be the key mechanism to understanding the relationship between eye movements and memory retrieval (Foos & Goolkasian, 2005), because attention determines which information is kept in working memory (Theeuwes et al., 2009). Future research should further investigate the role of visuospatial attention when explaining processes underlying looks directed at blank spaces.

Chapter 5 reported a study in which reasoning was studied with the help of verbal information – the chemical accident task. Other methods exist however to explore reasoning, such as the so-called "Black Box" paradigm used for example by Baumann (2000), Keinath (2002) and Johnson and Krems (2001) to study reasoning. In a typical Black Box trial, participants must locate four or five atoms hidden in a box by shooting light rays into the box and observing where the rays exit. The Black Box paradigm permits the manipulation of the complexity of the reasoning task and the causal patterns. The rules are fairly simple, but the paradigm allows for a high number of possible hypotheses, which consequently makes it a difficult task (Johnson & Krems, 2001). In a pre-study, Sascha Strehlau tested if memory indexing is also applicable to the Black Box paradigm. In an experimental investigation Strehlau (2014) found that unexplained symptoms, i.e. the atom could not be located, did not affect the final conclusion any differently from symptoms that were explained. Gaze data revealed that these unexplained symptoms were still kept in working memory in order to be processed. Memory indexing combined with the Black Box paradigm thus appears promising in the investigation of memory processes underlying more complex reasoning scenarios.

The experiments reported in this thesis assumed a cognitive process and measured eye movements to test process assumptions derived from the assumed processes. It would also be interesting to observe eye movements and deduce the underlying cognitive process from the gaze patterns. Recent attempts of this kind have lead to differing results (Orquin & Mueller Loose, 2013). Jahn and Braatz (2014) were however successful in predicting the final diagnosis from the gaze pattern shown during the first symptom presentation. A more sensitive experimental manipulation (see recommendations in section 6.2) might allow predicting cognitive processes by analyzing gaze behaviour.

This thesis combined the process tracing method, memory indexing, with outcome measures, like the decision to invite or reject a job candidate (Chapter 4) or the diagnostic response (Chapter 5). It could also be of further interest to combine memory indexing with other process tracing methods; for instance, memory indexing could be combined with functional imaging. Relating brain regions to memory-based thinking processes would allow for a detailed description of brain regions involved in thinking processes and allow for deeper insights into the functioning of these processes. Almost all manufacturers of eye tracking equipment now deliver appropriate hardware solutions (e.g. eye tracking glasses) to combine their equipment with functional imaging methods. To date, eye tracking has been mainly used to control for gaze behaviour in functional imaging studies (Holmqvist et al., 2011).

Besides providing fundamental knowledge of how eye movements interact with memory processes both during rather simple recognition as well as complex decision-making and reasoning tasks, the results from the experiments reported in this thesis also have implications for more applied strands of research.

A recent application of how knowledge about human decision-making, (i.e. the use of simple heuristics) can be used to guide diagnostic decisions has been demonstrated by Jenny and colleagues (Jenny, Pachur, Lloyd Williams, Becker, & Margraf, 2013). They applied a simple lexicographic fast and frugal decision tree as a tool to diagnose depression, and compared its performance to complex compensatory decision rules. The simple decision tree performed equally well to compensatory models. Such findings demonstrate how knowledge concerning the basic mechanism underlying human thinking can be used to develop reliable, simple, and therefore cost-efficient tutor-systems to guide a diagnostician’s decision.

Jarodzka et al. (2012) demonstrated how visual search can be enhanced with the help of eye tracking in order to train medical students. Case videos of patients were presented to experts and their eye movements were recorded. These eye movements were superimposed to the case videos and presented to students. The students’ visual search performance for relevant features, i.e. symptoms and their clinical reasoning performance for new cases were increased after being trained using the experts’ eye movement videos.

The human mind works as an information processor (Neisser, 1976). This metaphor has not only influenced and enhanced our understanding of the cognitive system but vice versa, when building information processing systems, the human mind serves as a role model to optimize such systems. Neubert, Görlitz, and Benn (2001) for example developed an adaptive index based on the similarity of objects that speed up data base requests.

This thesis aimed to investigate the looking-at-nothing behavior and possible applications to study memory-based thinking processes, thereby bringing together different strands of cognitive science: from perception and attention to reasoning and decision-making. Future research is necessary to further deepen the understanding of the fascinating interaction between eye movements, memory, and thinking to inform both cognitive and applied sciences.

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Yantis, S., & Jonides, J. (1981). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 937–947.

Yarbus, A. L. (1967). *Eye movements and vision* (trans. B. Haigh). New York: Plenum Press.

Curriculum Vitae

Agnes Scholz

Education

2009 – 2015 PhD candidate

2004 – 2009 Diplom in Psychology

Thesis: „Blickbewegungsmessung als Prozessmaß bei gedächtnisbasierten Multi-Attribut Entscheidungen" [Tracking eye movements as a process measure to study memory-based multi-attibute decisions]

Technische Universität Chemnitz, Germany
Supervisors: Josef F. Krems, Georg Jahn, Frank Renkewitz

Professional Experience

2009 – present Scientific Assistant

Department of Cognitive and Engineering Psychology,
Technische Universität Chemnitz, Germany

2013 (6 month) Visiting Researcher

Center for Economic Psychology
Prof. Dr. Jörg Rieskamp,
University of Basel, Switzerland

2006 – 2009 Research Assistant

Department of Cognitive and Engineering Psychology,
Technische Universität Chemnitz, Germany

Internship

2007 (4 month) Department of Transportation and Logistics
Dr. Katrin Dziekan,
Royal Institute of Technology (KTH), Stockholm, Sweden

Academic Workshops

2013 Statistical Computing using R with Gilles Dutilh
University of Basel, Switzerland

Analyses of Eye Movements with Linear Mixed Models using R with Reinhold Kliegl
European Conference on Eye Movements, Lund, Sweden

2011 Scientific Writing with Stefan Lang
Technische Universität Chemnitz, Germany

Mouse-Tracking with Jonathan B. Freeman, Rick Dale, and Michael Spivey
Annual Conference of the Cognitive Science Society, Boston, MA

2010 Summer School on Computational and Mathematical Modeling in Cognition of the European Society for Cognitive Psychology (ESCoP)
Mallnitz, Austria

2009 Winter School on Eye-Tracking Methodology
Universitat Autónoma de Barcelona, Spain

Grants and Prizes

2014 Student Poster award of the Society for Judgment and Decision Making
Annual Meeting, Long Beach, CA

2013 Research grant
granted by the German Academic Exchange Service (DAAD) for a sixth month research visit at the Centre for Economic Psychology, Basel, Switzerland

2012 Travel grant
granted by the German Academic Exchange Service (DAAD) for presenting research at the 34th Annual Conference of the Cognitive Science Society, Sapporo, Japan

Project

2011 – 2014 Diagnostic reasoning with causal models
(Prof. Dr. Georg Jahn, Prof. Dr. Josef F. Krems)
funded by the DFG (German Research Funding Organisation)

The goal of the project was to study diagnostic reasoning as a process of hypothesis generation and information integration based on causal knowledge. It focused on biases and memory dynamics that produce order effects in sequential symptom processing and on developing a suitable and unobtrusive method for tracing parallel belief updating.
Role: Graduate student

Teaching Experience

Lecture

2015 Cognition: Memory, problem solving, thinking, and language

Stand-in for lectures

2014 Eye movements and memory
2012 Diagnostic reasoning,
Problem solving phenomena and paradigms
2011 History of psychology,
Logical reasoning
2010 Theories of problem solving

Seminars

2014 Memory
2011 – 2014 Perception and attention
2010 – 2012 Thinking and problem solving
2009 – 2011 Practical seminar on empirical-experimental research

Supervised Student Work

Bachelor thesis

2014 Die Rolle des Arbeitsgedächtnisses bei der Symptomintegration im abduktiven Schlussfolgerungsprozess
[The role of working memory in the process of symptom integration during abductive reasoning] Sascha Strehlau

2013 Experimentelle Untersuchung zum Einfluss des Looking-at-nothing Phänomens auf die Erinnerung
[An experimental investigation of the relation between looking-at-nothing and memory retrieval] Lars Eberspach

Evaluierung räumlicher Darstellungsarten von Rasterkraftmikroskopie – Volumendaten hinsichtlich der Vermittlung fachrelevanter Inhalte
[Evaluation of spatial variants to display volume data with an atomic force microscope] Ines Thon

2012 Der Diversitätseffekt beim diagnostischen Schließen – Eine Eye-Tracking Studie
[The diversity effect in diagnostic reasoning – An eye tracking study] Ricarda Fröde

Der Einfluss von Aufmerksamkeitsverschiebung auf die Erinnerungsleistung im „Looking at nothing" – Paradigma
[Attention shifts affect retrieval performance in the looking-at-nothing paradigm]
Anja Prittmann

Master thesis

2014 Shifting covert attention to indexed locations increases retrieval performance of non-visuospatial material
Anja Prittmann

Research projects

2013 Datenerhebung mit Hilfe des Eye-Tracking Verfahrens
[Data collection with eye tracking] Judith Damm

Erstellung des Materials zur Untersuchung des Einflusses von Looking-at-nothing auf die Erinnerungsleistung
[Experimental material to study the functionality of the looking-at-nothing phenomenon]
Lars Eberspach

Anwendung und potenzielle Fehlerquellen des Eye Trackings in experimentellen Designs
[Eye tracking and experimental design: Methods and challenges] Nancy John

Methodische Umsetzung der Blickverhaltensanalyse im Black Box-Paradigma
[Eye tracking in the Black-Box paradigm] Sascha Strehlau

2012 E-Prime: Erste Hilfe Handbuch
[E-Prime: First aid] Stefanie Blechschmidt

2011 Einfluss von mentalem Workload und Lernstrategien auf das Auftreten des „Looking at Nothing“ Phänomens
[Mental workload assessment to study the looking-at-nothing phenomenon]
Ricarda Fröde

Publications

Journal Paper

Rebitschek, F. G., Bocklisch, F., Scholz, A., Krems, J. F., & Jahn, G. (2014). *Biased processing of ambiguous symptoms favors the initially leading hypothesis in sequential diagnostic reasoning.* Manuscript accepted for publication in Experimental Psychology.

Scholz, A., Krems, J. F., Jahn, G. (2014). *Watching diagnoses develop: Eye movements reveal symptom processing during diagnostic reasoning.* Manuscript submitted for publication.

Scholz, A., Mehlhorn, K., & Krems, J. F. (2014). Listen up, eye movements play a role in verbal memory retrieval. *Psychological Research.* http://dx.doi.org/10.1007/s00426-014-0639-4.

Scholz, A., von Helversen, B., & Rieskamp, J. (2015). Eye movements reveal memory processes during similarity- and rule-based decision making. *Cognition, 136,* 228–246. http://dx.doi.org/10.1016/j.cognition.2014.11.019.

Book Chapter

Scholz, A., Franke, T., & Platten, F. (submitted). Eye movements in vehicle control. In C. Klein, & U. Ettinger (Eds.), *An introduction to the scientific foundations of eye movement research and its applications*. Heidelberg: Springer.

Peer-Reviewed Conference Papers

Bocklisch, F., Bocklisch, S. F., Baumann, M. R. K., Scholz, A., & Krems, J. F. (2010). The role of vagueness in the numerical translation of verbal probabilities: A fuzzy approach. In S. Ohlsson & R. Catrambone (Eds.), *Proceedings of the 32nd Annual Conference of the Cognitive Science Society* (pp. 1974-1979). Austin, TX: Cognitive Science Society.

Rebitschek, F. G., Scholz, A., Bocklisch, F., Krems, J. F., & Jahn, G. (2012). Order effects in diagnostic reasoning with four candidate hypotheses. In N. Miyake, D. Peebles, & R. P.

Cooper (Eds.), *Proceedings of the 34th Annual Conference of the Cognitive Science Society* (pp. 905-910). Austin, TX: Cognitive Science Society.

Prittmann, A., Scholz, A., & Krems, J.F. (2015). *Shifting covert attention to spatially indexed locations increases retrieval performance of verbal information*. Manuscript accepted for publication in Proceedings of the Cognitive Science Society.

Scholz, A., Krems, J.F., & Jahn, G. (2015). Tracking memory processes during ambiguous symptom processing in sequential diagnostic reasoning. In N. Taatgen, M. van Vugt, J. Borst, & K. Mehlhorn (Eds.), *Proceedings of the 13th International Conference on Cognitive Modeling* (pp. 71-72). Groningen, NL: University of Groningen.

Scholz, A., Mehlhorn, K., Bocklisch, F., & Krems, J.F. (2011). Looking at nothing diminishes with practice. In L. Carlson, C. Hoelscher, & T.F. Shipley (Eds.), *Proceedings of the 33rd Annual Conference of the Cognitive Science Society* (pp. 1070-1075). Austin, TX: Cognitive Science Society.

Abstracts

Scholz, A., Krems, J.F., Jahn, G. (2015). Watching diagnoses develop: Eye movements reveal symptom processing during diagnostic reasoning. In M. Schulte-Mecklenbeck, J. Jarecki, & E. Söder (Eds.), *Proceedings of the Annual Meeting of the European Group of Process Tracing Studies* (p. 26). Berlin, Germany: MPI for Human Development.

von Helversen, B., Scholz, A., & Rieskamp, J. (2015). Eye movements reveal memory processes during similarity- and rule-based decision making. In M. Schulte-Mecklenbeck, J. Jarecki, & E. Söder (Eds.), *Proceedings of the Annual Meeting of the European Group of Process Tracing Studies* (p. 27). Berlin, Germany: MPI for Human Development.

Prittmann, A., Scholz, A., & Krems, J.F. (2015). Covert shifts of attention to indexed spatial locations increase retrieval performance of verbal materials. In C. Bermeitinger, A. Mojzisch, & W. Greve (Eds.), *Abstracts of the 57th Annual Conference of Experimental Psychologists* (p. 199). Lengerich: Pabst Science Publishers.

Scholz, A., Jahn, G., & Krems J. F. (2014). Tracking memory processes during sequential diagnostic
reasoning of ambiguous symptom information. In R. Maki (Ed.), *Proceedings of the 55th Annual Meeting of the Psychonomic Society* (p. 196). Long Beach, CA: Psychonomic Society.

Scholz, A., Jahn, G., & Krems, J. F. (2014). Tracking memory processes during dynamic updating of hypotheses in sequential diagnostic reasoning. In O. Güntürkün (Ed.), *Proceedings of the 49th Biennial Meeting of the German Society of Psychology (DGPs)* (pp. 32-33). Lengerich: Pabst Science Publishers.

Scholz, A., von Helversen, B., & Rieskamp, J. (2014, November). Eye movements reveal memory processes during similarity- and rule-based decision making. *Poster presented* *at the Annual Conference of the Society for Judgment and Decision Making,* Long Beach, CA.

Scholz, A., von Helversen, B., & Rieskamp, J. (2014). Tracking memory processes during rule- versus similarity-based decision making. In Schütz, A.C., Drewing, K., & Gegenfurtner, K.R. (Eds.), *Abstracts of the 56th Conference of Experiemental Psychologists* (p. 237). Lengerich: Pabst Science Publishers.

von Helversen, B., Scholz, A., & Rieskamp, J. (2014). Eye movements reveal memory processes during similarity- and rule-based decision making. In R. Maki (Ed.), *Proceedings of the 55th Annual Meeting of the Psychonomic Society* (p. 58). Long Beach, CA: Psychonomic Society.

Scholz, A., Jahn, G., Rebitschek, F. G., & Krems, J.F. (2013). Diversity influences hypothesis selection in sequential diagnostic reasoning: A process tracing study. In U. Ansorge, E. Kirchler, C. Lamm & H. Leder (Eds.), *Abstracts of the 55th Conference of Experiemental Psychologists* (p. 253). Lengerich: Pabst Science Publishers.

Scholz, A., & Johansson, R. (2013). Special symposium on eye movements to blank spaces during memory retrieval. *17th European Conference on Eye Movements*, Lund, Sweden.

Scholz, A., & Krems J. F. (2013). Covert shifts of attention decrease retrieval performance while fixating blank locations. In K. Holmqvist, F. Mulvey & R. Johansson (Eds.), *Book of Abstracts of the 17th European Conference on Eye Movements*, *11-16 August 2013, in Lund, Sweden.* Journal of Eye Movement Research, 6(3), 287.

Scholz, A., Mehlhorn, K., & Krems J. F. (2013). Eye movements to blank spatial locations influences memory retrieval for auditory information. In E. Loftus (Ed.), *Proceedings of the 54th Annual Meeting of the Psychonomic Society* (p.123). Toronto, Canada: Psychonomic Society.

Scholz, A., Mehlhorn, K., & Krems, J. F. (2012). Looking at nothing facilitates memory retrieval. In N. Miyake, D. Peebles, & R. P. Cooper (Eds.), *Proceedings of the 34th Annual Conference of the Cognitive Science Society* (p. 2855). Austin, TX: Cognitive Science Society.

Scholz, A., Mehlhorn, K., & Krems, J. F. (2012). Impairing "looking at nothing" decreases performance. In A. Bröder, E. Erdfelder, B.E. Hilbig, T. Meiser, R.F. Pohl, & D. Stahlberg (Eds.), *Abstracts of the 54th Conference of Experiemental Psychologists* (p. 116). Lengerich: Pabst Science Publishers.

Scholz, A., & Krems J. F. (2011). Guiding eyes away from previous locations of information presentation impairs retrieval of semantic information. In F. Vitu*, E.* Castet*,* & L. Goffart, (Eds.) (2011). *Abstracts of the 16th European Conference on Eye Movements, Marseille, 21-25 August 2011.* Journal of Eye Movement Research, 4(3), 32.

Scholz, A., Mehlhorn, K., & Krems J. F. (2011). Eye movements reflect information search in memory during diagnostic reasoning. In N. Newcombe (Ed.), *Proceedings of the 52nd Annual Meeting of the Psychonomic Society* (p. 229). Seattle, WA: Psychonomic Society.

Scholz, A., Mehlhorn, K., Ruthsatz, A., & Krems, J. F. (2011). Die Suche nach Informationen im Gedächtnis führt zu Blickbewegungen an den Ort der Informationsaufnahme [Information search in memory leads the gaze back to associated spatial locations]. In K. Bittrich, S. Blankenberger & J. Lukas (Eds.), *Abstracts of the 53th Conference of Experiemental Psychologists* (p. 158). Lengerich: Pabst Science Publishers.

Scholz, A., Jahn, G., Renkewitz, F., & Krems, J. F. (2010). Blickbewegungsmessung als Prozessmaß bei gedächtnisbasierten Multi-Attribut-Entscheidungen [Tracking eye movements as a process measure to study memory-based multi-attibute decisions]. In C. Frings, A. Mecklinger, D. Wentura & H. Zimmer (Eds.), *Abstracts of the 52th Conference of Experiemental Psychologists* (p. 289). Lengerich: Pabst Science Publishers.

Dziekan, K., & Scholz, A. (2007, September). How to measure ease-of-use in public transport? Scale construction and testing. *Poster presented at the Biennial Conference on Environmental Psychology*, Bayreuth, Germany.

Workshops and Invited Talks

Scholz, A. (2015, February). A one-day introductory workshop on eye tracking methodology, *University of Basel*, Basel, Switzerland.

Scholz, A. (2014, May). Tracking memory processes during rule versus similarity-based decision making. *Research colloquium (Prof. Dr. Peter Sedlmeier)*, Technische Universität Chemnitz, Germany.

Scholz, A. (2013, November). Eye movements in memory-based processes of information search. *Research colloquium (Prof. Dr. John Anderson),* Carnegie Mellon University, Pitssburgh, PA.

Scholz, A. (2013, July). Tracking memory-processes in similarity-based multi-attribute decisions. *Research colloquium (Prof. Dr. Arndt Bröder),* University of Mannheim, Germany.

Fiedler, S., & Scholz, A., (2012, August). Introductory lesson on Eye tracking Methodology. *4th Workshop of the junior research group on decision making*, Basel, Switzerland.

Scholz, A., Mehlhorn, K., & Krems, J. F. (2012, May). Impairing "looking at nothing" decreases performance. *6th Scandinavian Workshop on Applied Eye Tracking*, Stockholm, Sweden.

Scholz, A. (2011, June). Die Suche nach Informationen im Gedächtnis führt zu Blickbewegungen an den Ort der Informationsaufnahme [Information search in memory leads the gaze back to associated spatial locations]. *Research colloquium (Prof. Dr. Fred Hamker),* Technische Universität Chemnitz, Germany.

Scholz, A., Jahn, G., Renkewitz, F., Krems, J. F. (2010, September). Tracking memory search for process tracing in multi-attribute decision making. *3rd Workshop of the junior research group on decision making*, Basel, Switzerland.

Scholz, A. (2010, July). Cognitive processes in diagnostic decision making. *Poster presented at the 1st ESCOP Summer School in Computational and Mathematical Modeling of Cognition*, Mallnitz, Austria.

Scholz, A., Mehlhorn, K., & Krems, J. F. (2010, May). Practice eliminates "looking at nothing". *5th Scandinavian Workshop on Applied Eye Tracking*, Lund, Sweden.